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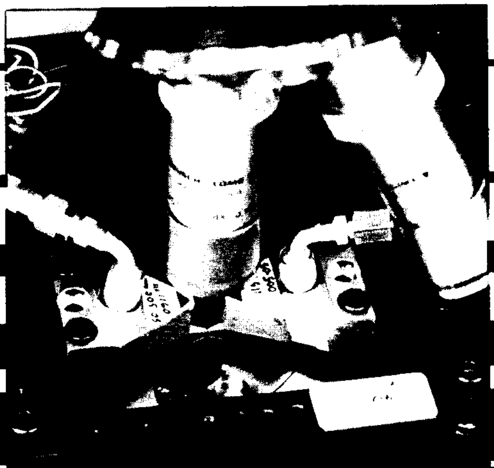
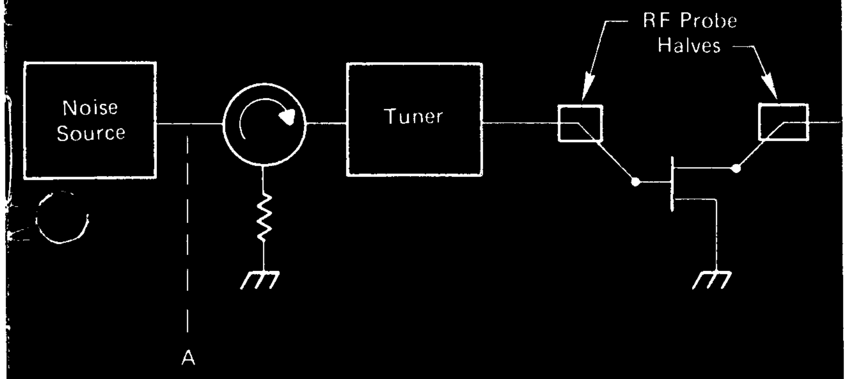
Automated Noise-Parameter Measurements Using A Microwave Probe





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The noise and S-parameters of a GaAs field-effect transistor (FET) contain information that engineers need to design low-noise microwave amplifiers. For this reason, fast, accurate methods of determining these parameters can greatly reduce the cost of amplifier development. The advent of the microwave probe has already made S-parameter measurements both rapid and nondestructive, since probes permit measurement directly on FET wafers using automated instruments. Much incentive, therefore, exists for the development of automated techniques for measurement of chip-level noise parameters using a microwave probe.

This article describes one such technique, and it presents measurement results. The method used is one of measuring the FET noise figure at several distinct values of source admittance. A special calibration sequence provides the information needed to reference all noise figures and source admittances to the FET chip. Automation is accomplished through the use of standard microwave instruments in combination with an automated source admittance tuner.

Along with outlining the principles behind the measurement, the article describes a special source admittance tuner. This tuner has the advantages of being particularly simple to build and easy to interface to a digital controller.

The overall measurement method, however, can be adapted to any of a variety of source tuning methods.

Measuring Noise Parameters

The noise figure of an FET varies with the source admittance driving it, according to a well-known mathematical relationship. Equation 1 expresses the relationship in a form which is convenient for circuit design:

$$F = F_o + R_n \left| Y_s - Y_o \right|^2 / G_s \qquad (1)$$

where F is the FET noise figure; Y_s is the source admittance; G_s is the source conductance; and F_o, Y_o, and R_n are the noise parameters. Y_o is the source admittance for which F attains its minimum value F_o. R_n has dimensions of resistance, and describes the rate at which F increases as Y departs from Y_o. The noise parameters can be functions of frequency, dc bias, temperature, and other factors.

Finding the noise parameters of a FET usually involves measuring the noise factor at one or more values of source admittance. Figure 1 is a block diagram of a measurement system, based on use of a microwave probe, which is suitable for noise-parameter measurement. A meter displays noise figure, while a tuner in front of the FET permits variation of Y_s. The figure shows that the system also employs a calibrated noise source, two isolators to control the effects of mismatch, a postamplifier, and a filter/mixer combination for single-sideband downconversion. The planes A and B in Figure 1 are the locations of coaxial connections which serve as reference planes for noise figure and admittance measurements.

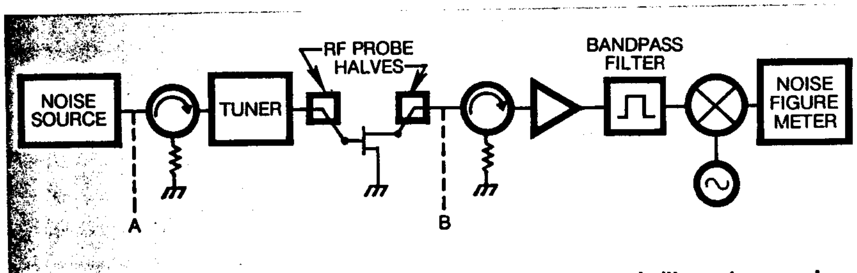

Figure 1. On-wafer noise-parameter measurement uses a source admittance tuner and an rf probe for contact to the FET under test. Noise-figure measurements are calibrated to planes A and B.

One way of using the system of Figure 1 is to adjust the tuner until the noise-figure measurement reaches its minimum. At this point, F and Y_s would presumably be equal to F_o and Y_o. Results of a second measurement at some other Y_s would determine R_n. Though simple in concept, this approach has several drawbacks for use in automated measurement of noise parameters. These include the necessity of tuning exactly onto Y_o in order to make an accurate measurement; the possibility of missing the minimum for the FET due to variations in tuner loss; and the difficulty of finding a shallow minimum using an automated search.

A better approach is to measure F at several distinct values of Y_s. Substituting the resulting information into equation 1 then determines the noise parameters. In principle, four measurements can yield enough information to determine the four scalar quantities in the noise parameters. In practice, workers usually make more than four measurements and perform some kind of averaging in order to lessen the effects of measurement error (1).

Measurement Strategy

Some inherent difficulties in using the system of Figure 1 arise because the reference planes A and B are not at the terminals of the FET itself. As a result, raw noise-figure measurements made with the system always include the tuner and the probe along with the FET. Furthermore, no admittance measurement at planes A and B can determine Y_s directly, since the reference plane for Y_s is at the gate-side probe tip.

Referencing results to the FET requires use of the proper measurement approach. In considering an approach, it is useful to divide the network between planes A and B into three sections. The first section is the input network extending from plane A to the gate-side probe tip. The second section is the FET itself. The third section is the output network extending from the drain of the FET to plane B.

A well-known equation relates the noise figure of the three sections in cascade to the noise figures and available gains of the individual sections:

$$F_c = F_1 + (F_2 - 1) / G_1 + (F_3 - 1) / G_1 G_2 \qquad (2)$$

where F_c is the noise figure of the entire cascade, F_1, F_2 or F_3 is the noise figure of the corresponding section, and G_1, G_2 or G_3 is the available gain of that section. In equation 2, the quantity of interest is F_2, the noise factor of the FET chip. Solving for F_2 from the measured noise factor, F, requires knowledge of F_1, F_3, G_1, and G_2.

Under certain conditions, the S-parameters of the three cascade sections contain enough information to determine F_2. The S-parameters, together with the output admittance of the noise source, determine G_1, G_2, and G_3. G_1 and G_3, in turn, determine F_1 and F_3, provided the input and output sections are passive networks. The noise figure of a passive network with available gain G_n is simply,

$$F_n = 1 + \frac{(1 - G_n)\, T_n / T_o}{G_n} \qquad (3)$$

where T_n is the temperature of the network and T_0 is the standard temperature (usually 290K).

Impedance mismatch at plane B in Figure 1 complicates the determination of F_c. The effect of mismatch is to change the available gain and the noise figure of the output isolator. The noise-figure meter cannot distinguish between this change and noise actually generated by the cascade between planes A and B(2). Assuming the reverse transmission of the isolator and the reflection coefficient of noise source are neglegible, the correction to a measured F for mismatch is,

$$F_c = F_c' - \frac{(F'(X_c/X - 1/X) - (1 - 1/X))}{G_1G_2G_3} \tag{4}$$

In equation 4, F_c is the correct noise figure, and F_c' is the noise figure displayed by the calibrated noise-figure meter. F is the noise figure measured at calibration of the noise-figure meter, when the noise source is connected directly to plane B. X_c and X are functions of the mismatch loss during calibration and measurement. X_c is given by,

$$X_c = 1 + \frac{(1 - M_c)\,T_i/T_o}{M_c} \tag{5}$$

where T_i is the temperature of the isolator, X is a similar function involving a quantity M, and M_c and M are the mismatch "gains":

$$M_c = 1 - |\Gamma_i|^2 \tag{6}$$

$$M = \frac{(1 - |\Gamma_n|^2)\,(1 - |\Gamma_i|^2)}{|1 - \Gamma_n \Gamma_i|^2} \tag{7}$$

where Γ_i is the input reflection coefficient of the isolator and Γ_n is the output reflection coefficient of the three-part network. M_c and M can be calculated from the S-parameters of the three sections and the input admittance of the isolator.

The second part of the measurement process is to determine Y_s. In the case of the system in Figure 1, Y_s is the output admittance of the gate-side probe tip. This is easy to determine from the S-parameters and the noise source admittance. Thus, the problem of finding the FET noise figure and the corresponding source admittance can be equivalent to that of measuring the overall noise figure, the S-parameters of the three cascade sections, and the input admittance of the isolator at plane B.

Measuring S-Parameters

Determining the S-parameters of the three network sections of Figure 1 is central to an on-wafer noise parameter measurement. Techniques for on-wafer measurement of FET S-parameters are well known, so they need not be discussed here. Measuring the S-parameters of the input and output sections is possible through a particular sequence of steps.

Figure 2 is a schematic diagram of a system for measuring the input and output S-parameters. The network of Figure 1 has been broken at the reference planes A and B, and these planes have been made available for connection to an automatic network analyzer (ANA). The process of measurement makes use of two sets of impedance standards: a coaxial set for calibration of the ANA and a planar set to serve as references for the microwave probe.

The first step in S-parameter measurement is to calibrate the ANA using coaxial standards and connect it to planes A and B of the measurement network. The second step is to measure the S-parameters of the output section. This consists of placing the drain probe on three different one-terminal planar standards and measuring the corresponding reflection coefficients at plane B. Since the output network is reciprocal, the three reflection coefficient measurements yield enough information to determine its S-parameters (3,4).

The third step is to measure the S-parameters of the input section for all tuner settings of interest by placing the probe on a planar through line, stepping the tuner through its settings, and measuring S-parameters at planes A and B. This information, together with the electrical length of the through line and the information from the second step, determines the S-parameters of the input section.

The overall measurement procedure for obtaining noise parameters is as follows: First, connect the ANA directly to the microwave probe, calibrate, and measure the S-parameters of each FET of interest. Then, assemble the input isolator and tuner to the gate side of the probe. Next, perform the calibration and measurement steps which determine the S-parameters of the input and output network sections. Finally, probe each FET and measure noise figure at all tuner settings of interest. This process is simple to extend over any desired frequency range.

Automating the Measurements

The (Y_s, F) data points which determine FET noise parameters result from a series of S-parameter and noise-figure

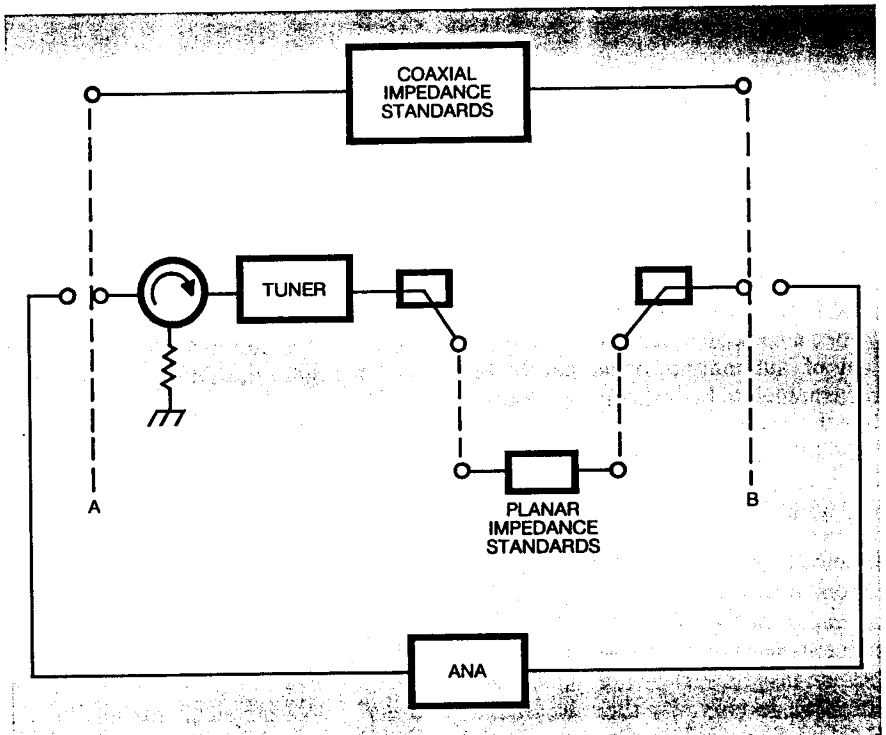

Figure 2. S-parameter measurements use an automatic network analyzer and two sets of impedance standards.

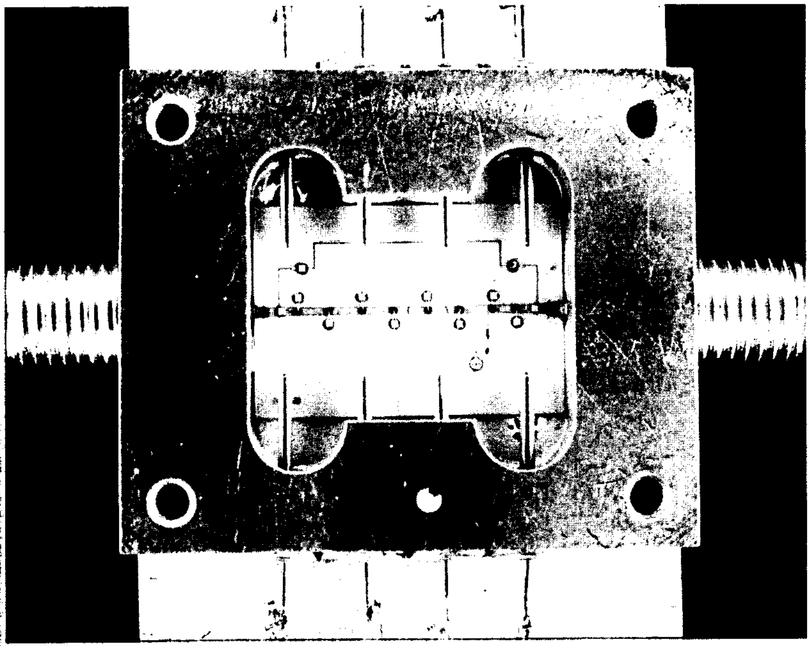

Figure 3. The PIN diode tuner is simple and compact.

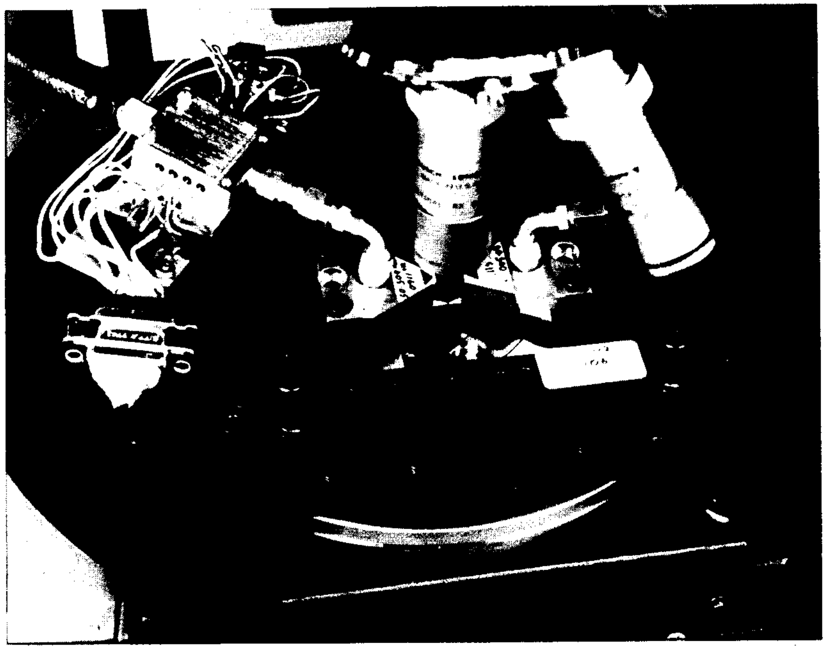

Figure 4. The small size of the tuner permits close proximity to the rf probe heads.

measurements. The time and labor costs associated with these measurements are high, unless the measurements can be automated. Today, it is possible to collect S-parameter and noise-figure data from automated instruments under the direction of a computer. Therefore, the problem of automating noise parameter measurements boils down to automating the operation of the source tuner. The tuner should be fast and simple to use, and its settings should be highly repeatable.

Figure 3 shows a photograph of an automated tuner which is well-suited for noise-parameter measurement(5). The tuner consists of a microstrip through line and eight PIN switching diodes. Each diode chip sits directly on the through line, and its dc bias wire is grounded through a capacitor. Switching a diode on or off switches shunt inductance into or out of the microwave circuit. Switching combinations of diodes allows the tuner to map the admittance of a noise source into a number of different output admittances. Figure 4 is a photograph of the tuner being used in conjunction with a microwave probe.

The tuner has a number of advantages for the noise-parameter measurement application. First, it is very simple to build, since precise tuning of the shunt inductance values is unnecessary for tuner function. Second, it is easy to control; an eight-bit digital word with suitable buffering switches the diodes on and off. Third, the tuner is light and compact, making it possible to mount the tuner in close physical proximity to the probe, minimizing cable loss. Last, measurements show that the the tuner obeys equation 3 at microwave frequencies.

Since the tuner contains eight switching diodes, it has 256 distinct states. In practice, the 37 states which involve turning on two or fewer of the diodes are the most useful. For these states, the insertion loss of the tuner is low enough to permit accurate measurement of the corresponding FET noise figures.

Measurement Results

The tuner shown in Figure 3 has been used with standard test equipment to perform automated, on-wafer noise parameter measurements on a GaAs FET. The measurement and data reduction process already outlined resulted in (Y_s, F) data over a range of frequencies. The noise parameters were found by fitting equation 1 to the measured data using a least-squares technique.

Figures 5 and 6 show results from on-wafer noise-parameter measurement in X-band. The FET involved in these measurements is a general-purpose device manufactured by Watkins-Johnson Company, having .5-μm gate length and 200-μm gate width. The dc bias current was 15 mA with a drain-source voltage of 3 V.

Figure 5 shows source admittance and noise-figure data collected at 8 GHz. Data points with noise figures greater than 6 dB have been omitted for clarity. The figure also shows the minimum noise figure, optimum-source admittance, and several noise-figure circles in accordance with the fitted noise parameters. The optimum point and the noise-figure circles agree very well with the measured data. Figure 6 is a plot of Y_o over frequency as determined from measurement results.

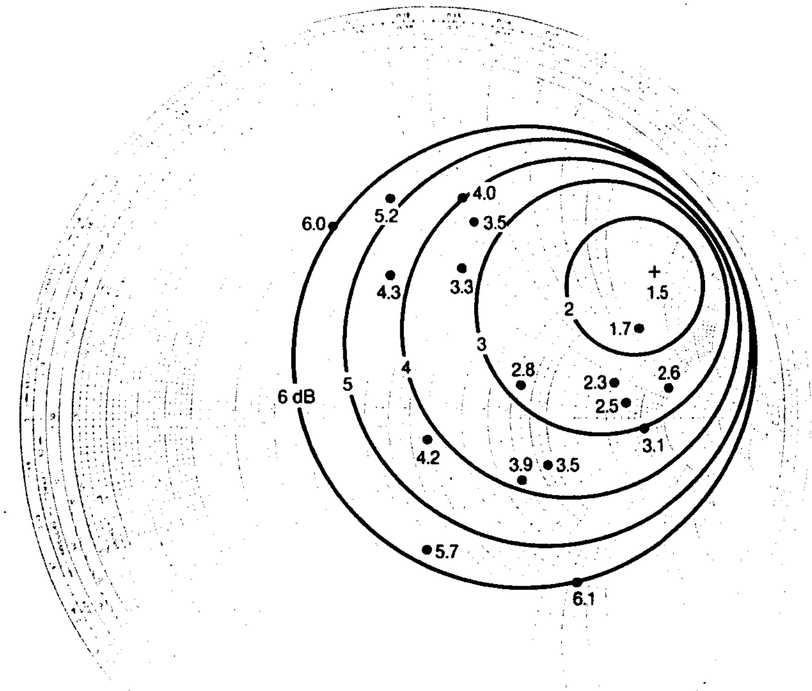

Figure 5. The measured data (Y_s, F) compare well with the noise-figure circles and the optimum predicted by the fitted noise parameters. (● = measured point; + = predicted optimum. Results are from a general purpose, 200 × .5 μm GaAs FET with Vds = 3 V, Ids = 15mA, and F = 8 GHz.)

Further Development

The results in Figures 5 and 6 show that on-wafer noise-parameter measurement can be practical and accurate. While the switched tuner represents but one of a number of possible techniques for tuning Y_s, it is simple to use and it produces good results. At the same time, however, further refinement of the tuner and of noise-parameter measurement in general are possible. Commercial vendors have announced products which integrate a source tuner and a microwave probe into one package. In addition, recently published theory (6, 7) suggests that the whole noise parameter measurement process can be simplified.

The small size of the switched diode tuner suggests that it could fit on the circuit card of the gate side of the microwave probe. If it also included switching between direct and tunable transmission paths, the resulting probe/tuner card would be useful for both S- and noise-parameter measurements. Separate coaxial inputs would connect the card to the network analyzer and to a noise source. Following suitable calibration, it would be possible to perform a complete S and noise characterization of a FET

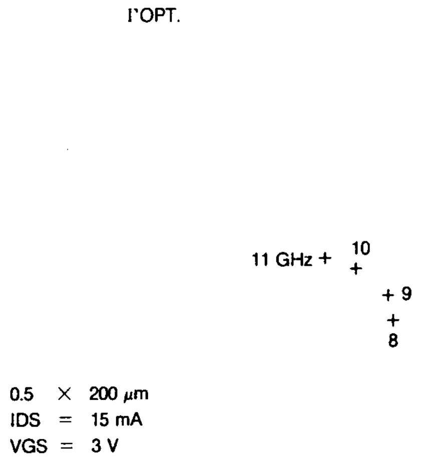

Figure 6. Results of stepped measurements show Γ optimum as function of frequency.

without making or breaking coaxial connections.

Recent articles outline a shortcut approach to noise parameter measurements(6,7). The approach uses broadband S-parameters plus a single-frequency measurement of output noise power. Under certain assumptions, these convey enough information to determine the noise parameters over much of the microwave frequency range. If it gains general acceptance, this approach is likely to come into widespread use. The shortcut approach can make use of the measurement procedure of this article. Instead of measuring output noise power as suggested in references 6 and 7, one could measure the noise parameters at a single frequency. This information, together with broadband S-parameters, is sufficient to determine the elements in the FET noise model presented by the references. Thus, performing the tuner calibration and measurement sequence at only one frequency would yield broadband noise parameters. The advantage of using the technique of this article is that it references all measurements to the FET chip level in an unambiguous way.

This article has described a method for automated, on-wafer measurement of GaAs FET noise parameters. The method makes use of standard instruments together with a simple automated tuner, though it is adaptable to other means of source tuning. With this method, FET manufacturers can evaluate their low-noise devices before wafer separation, and they can supply design engineers with accurate, chip-level noise parameters at lower cost than before.

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