CHARACTERIZATION OF MESFET AND MODFET MICROWAVE NOISE PROPERTIES UTILIZING DRAIN NOISE CURRENT [1]

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ABSTRACT

The microwave drain noise characteristics have been studied for conventional long gate (1.0 μm and 0.5 μm) GaAs MESFET's and short ($\approx 0.15\ \mu m$) strained InGaAs/InAlAs/InP MODFET's. Although the MODFET's have lower noise figures ($F_{min} \approx 0.4$dB at 10GHz) than the MESFET's (1.5dB at 10GHz), their measured drain noise currents are greater indicating that F_{min} does not describe the true device noise characteristics. Due to higher gain, estimated parastic contribution to the device noise is greater for the MODFET's than the MESFET's. The intrinsic channel noise has been modelled with an effective temperature associated with r_{ds}, showing that carrier heating alone cannot explain the measured characteristics.

INTRODUCTION

Modern FET's provide mininum noise figures, F_{min}, on the order of 0.5 dB at X-band. The noise characterization of FET's is typically limited to the noise parameters: F_{min}, R_n, and Γ_{opt}. More specifically, F_{min} is used to indicate whether a device is more or less noisy than another device. F_{min} is applicable to circuit work, however, it fails to describe just the noise of the device. Instead, it lumps together device gain and noise to provide a measure of the degradation of the signal-to-noise ratio. In order to completely understand the origin of the excellent F_{min}'s of today's modern FET's it is necessary to look at the actual noise of the device. Theoretical modeling concentrates on the noise parameters without providing extensive discussion on the intrinsic noise behavior. Some experimental work has been done, in the past, by Folkes [1] and Gupta [2]. However, it was constrained to GaAs MESFET's. This work provides a more comprehensive picture of FET noise properties by describing the microwave noise characteristics of FET's in terms of their measured intrinsic noise. State-of-the-art MODFET's are characterized and compared with conventional longer gate MESFET's. This comparison is used to contrast the fundamental differences in the actual noise of the devices. The results of this work show the dependence of the noise on drain current, drain voltage, and gate length. In addition, the noise of different device structures (MESFET's and MODFET's) is compared.

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NOISE CHARACTERIZATION APPROACH

The devices are characterized in terms of their total drain noise, i_{dn}. The origins of i_{dn} include the following: (i) intrinsic noise in the channel region, i_{dsn}, which is the result of high field diffusion noise ([2], [3], [4] and [5]) and (ii) the parasitic elements consisting of the gate metal resistance, r_g, the intrinsic resistance, r_i, the source resistance, r_s, and the drain resistance, r_d. The contribution of the parasitics is represented as Johnson noise with the elements at the ambient temperature, T_a. r_i is included here as a parasitic since it represents the charging time resistive component and it should add some amount of Johnson noise as is done by Pospieszalski [6]. The contribution due to the induced gate noise is assumed to be negligible since: (i) its absolute value is quite small [7], and (ii) the gate is terminated into an approximate short circuit.

It can be shown that the total drain noise current can be determined from the DUT noise factor and its S-parameters using the expression:

$$\overline{i_{dn}^2} = (F_{DUT} - 1) k_B T_0 G_{av,DUT} 4 Re\left(Y_0 \frac{1 - S'_{22,DUT}}{1 + S'_{22,DUT}} \right) \quad (1)$$

where: F_{DUT} is the DUT's noise factor when it is terminated into an approximate short circuit, $G_{av,DUT}$ is the DUT's available gain, and $S'_{22,DUT}$ is the output reflection coefficient of the device when it is terminated into Γ_t ($\Gamma_t \rightarrow$ -1).

Knowledge of the DUT's S-parameters will permit extraction of the equivalent circuit parameters and estimation of i_{dsn} by removing the contribution of the parasitics from i_{dn}. To enhance the accuracy of the estimates of the parasitics, a special parameter extraction procedure was developed for the MODFET structures.

The noise measurements were made at 1.5GHz to ensure that the devices were well out of the 1/f noise region, yet within the white noise regime. Such a high frequency is required to ensure testing outside the 1/f noise region which for MODFET's is known to extend well up to several hundred MHz [8].

DEVICE CHARACTERISTICS

Two categories of device were used in this work. The first was ion implanted GaAs MESFET's having gate geometries of $0.5\mu m \times 300\mu m$ and $1.0\mu m \times 300\mu m$. The sec-

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ond was MODFET's fabricated using the InGaAs/InAlAs/InP material system. This is a very promising material system for high frequency applications. These devices had gate geometries of $0.15\mu m \times 90\mu m$. The reason for using such devices is to determine the intrinsic differences between FET's which have dramatically different terminal characteristics. The noise parameters were determined for these devices using a cold noise power technique, [9]. The measured F_{min} of different devices is shown in figure 1. Two outstanding features are observed. First, as shown in Figure 1, the F_{min} decreases with decreasing gate length, which is well known. Second, the MESFET's have a very well defined F_{min} at very low I_{DS}. The same is not true for the MODFET's which demonstrate a very broad noise minimum in comparison. Moreover, the minimum value for F_{min} of the MODFET occurs near I_{DSS} (I_{DSS}=I_{DS} with V_{GS}=0V). The minimum F_{min} of the longer gate MESFET's occurs in the region of $I_{DS}=0.1I_{DSS}$.

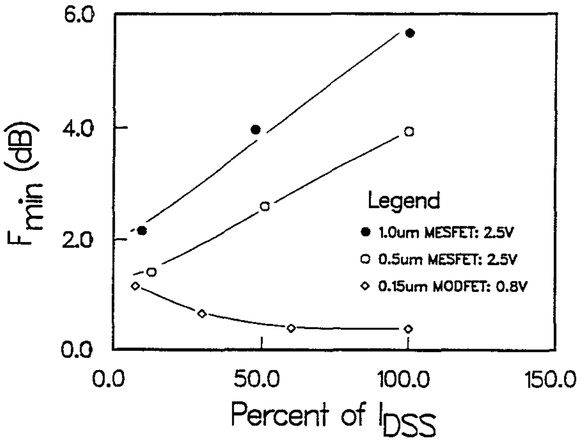

Figure 1: Measured F_{min} as a function of bias at 11GHz.

MEASURED DRAIN NOISE CHARACTERISTICS OF THE MESFET'S AND MODFET'S

The drain noise, i_{dn}, was measured at different bias points in saturation. The drain noise current was measured for the different MESFET structures for 10, 50 and 100 percent of I_{DSS} at V_{DS}=1.25V and 2.5V. Experimental results are shown in Figure 2. A linear dependence on I_{DS} was obtained for both devices, in agreement with physical studies of FET noise [4], [5]. In contrast, the devices had no V_{DS} dependence. The $\overline{i_{dn}^2}$ of the $0.5\mu m$ device was greater than that for the $1.0\mu m$ device for all bias conditions. The contribution of the parasitics, also included in the plot, is small, contributing no more than about 15 percent of the total measured drain noise. We can conclude that i_{dn} is almost entirely made up of intrinsic noise, i_{dsn}.

The F_{min} increased with increasing I_{DS} as did $\overline{i_{dn}^2}$. F_{min} increased slightly with increasing V_{DS} which contrasts with $\overline{i_{dn}^2}$. In addition, the F_{min} of the $0.5\mu m$ device was less than that of the $1.0\mu m$ device. This also contrasts with what was observed for $\overline{i_{dn}^2}$. This clearly shows that

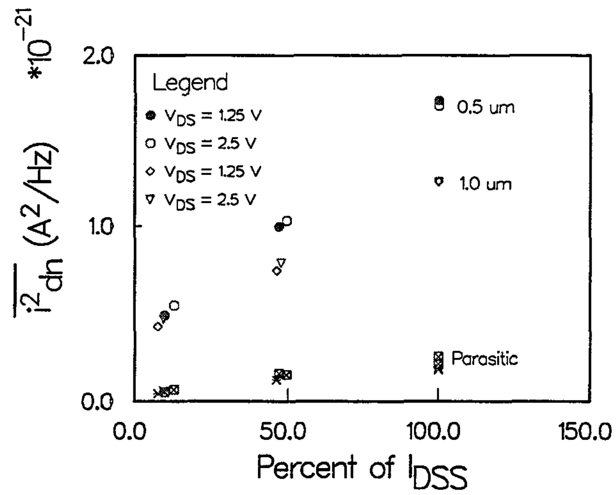

Figure 2: Measured $\overline{i_{dn}^2}$ as a function of bias for the $1.0\mu m$ and $0.5\mu m$ MESFET. Parasitic contribution is also shown.

the device noise figure is not a direct representation of the intrinsic device noise.

The $\overline{i_{dn}^2}$ of the MODFET's was measured over bias ranges corresponding to V_{DS}=0.6V, 0.8V, 1.0V, 1.2V with I_{DS} varied from $< 0.1I_{DSS}$ to I_{DSS} (V_{GS}=0V). $\overline{i_{dn}^2}$ increases monotonically with I_{DS}. At very high drain currents and voltages, the noise begins to increase more rapidly. The parasitic contribution to the total drain noise is about 50 percent for $V_{DS} = 0.6V$ and $0.8V$. This is mainly due to very high device gain, amplifying the noise contribution of the input parasitics. However, based on this modeling, the relative parasitic contribution decreases at increased V_{DS} and I_{DS}. For instance, it decreases to about 27 percent at $V_{DS} = 1.2V$ and $I_{DS} = 23mA$. The slight decrease in the parasitic contribution is due to the decrease in r_i at higher V_{DS}. Figure 3 shows the extracted i_{dsn}. In all cases, the i_{dsn} is greater than the parasitic contribution. Moreover, at high bias conditions (V_{DS}= 1.0V and 1.2V) the i_{dsn} undergoes dramatic increases. This trend can be affected by the accuracy of the parasitic resistances of the equivalent circuit. However, a dramatic increase in drain noise is also seen in $\overline{i_{dn}^2}$ at large V_{DS} and I_{DS}. In contrast to the noise currents, F_{min} increases with decreasing I_{DS}. This demonstrates that the actual noise characteristics of the device are not described by F_{min}.

COMPARISON OF THE DEVICES AND INTERPRETATION OF NOISE CHARACTERISTICS

In order to compare the devices the noise must first be normalized to the gate width. Figure 4 is a comparison of the normalized drain noise currents, $i_{dn,N}^2$. Over virtually the entire bias range the MODFET noise is greater than that of the MESFET. The noise becomes comparable in the very low I_{DS} range. The MESFET noise is a function of I_{DS} but it is essentially V_{DS} independent. The MODFET

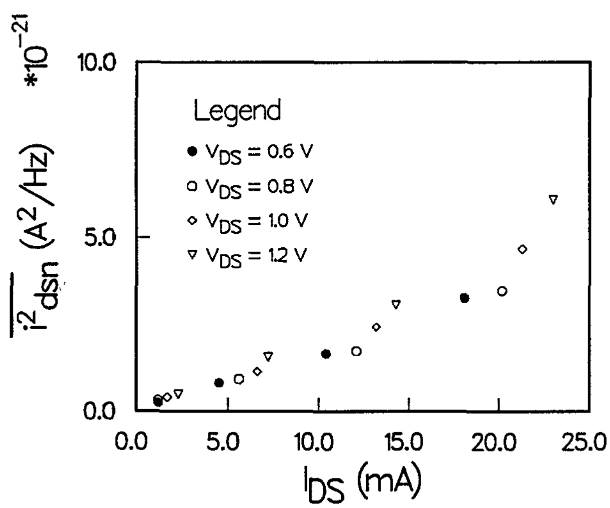

Figure 3: Extracted $\overline{i^2_{dsn}}$ as a function of bias for the $0.15\mu m$ MODFET.

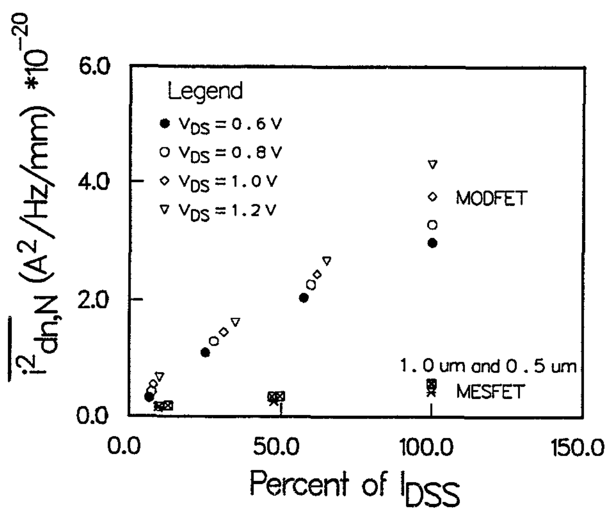

Figure 4: Measured $\overline{i^2_{dn}}$ (normalized to the gate width) as a function of bias for the short gate length MODFET and the longer gate MESFET's. V_{DS} of the MODFET is shown. V_{DS} of the MESFET's is 1.25V and 2.5V

noise is also a function of I_{DS}, however, it also appears to have a V_{DS} dependence.

The bias dependence of the noise in the MESFET's can be readily interpreted using the physical noise model presented in [4], [5]. The noise current source, of the individual channel subsections is expressed as:

$$\overline{\Delta i_j^2} = 4q^2 D_{\|} N_j Z/\Delta x, \quad (2)$$

where q is the charge of a carrier, j indicates the $j-th$ channel section, of length Δx, N_j is the carrier density, Z is the device width and $D_{\|}$ is the diffusion coefficient parallel to the channel. We note that the noise is proportional to the carrier density. As the gate voltage is varied to increase the amount of charge below the channel, I_{DS} increases and so does the measured noise. In order to understand the absence of any V_{DS} dependence the average electric field, E, is estimated using:

$$E = \frac{V_{DS}}{L_g} \quad (3)$$

Where: L_g is the gate length. The E ranges over $12.5kV/cm \leq E \leq 25kV/cm$ and $25kV/cm \leq E \leq 50kV/cm$ for the $1.0\mu m$ and $0.5\mu m$ MESFET's, respectively. In this region we can approximate $D_{\|}$ as constant (Figure 4 in [5]). This is the only parameter through which the drain bias will affect equation (2). As a result there is no V_{DS} dependence.

The bias dependence of the MODFET is far more involved. E ranges from $40.0kV/cm \leq E \leq 80.0kV/cm$. Using the above arguements, the bias dependence in terms of I_{DS} at a fixed V_{DS} can be interpreted in the same way as the MESFET. However, from the electric field considerations we would not expect any V_{DS} dependence. This contradicts what was measured. There are two possible reasons for this. First, short channel effects may be playing a role [10]. The drain voltage may in fact be modulating the total charge in the channel. This would give rise to increased noise through the N_j term in equation (2). Second, the conduction mechanism could be changing. These MODFET's have breakdown voltages less than 2V. As the breakdown voltage is approached, additional noise could be generated by the associated breakdown mechanism.

Consideration of equation (2) also helps understanding the larger intrinsic noise observed in MODFET's with respect to MESFET's, since MODFET channels feature larger carrier densities due to heavy donor layer doping. Moreover, our MODFET's have shorter channels than the MESFET's and this turns out to contribute to their high noise current. The rather surprising increase of noise current in shorter gate length devices (see Figure 2) can be explained in the following way. The equations in [4] and [5] for the drain noise voltage and current need to be solved numerically in the MESFET and MODFET cases but can be solved analytically in the simplified case of a resistor, resulting in:

$$\overline{v_{dn}^2} = \Sigma_j \overline{\Delta i_j^2} \cdot \Delta R^2 = \overline{\Delta i_j^2} \cdot N \cdot \Delta R^2, \qquad \overline{i_{dn}^2} = \frac{\overline{v_{dn}^2}}{R^2}, \quad (4)$$

where the resistance R is subdivided into N sections, ΔR, and represents the case of a uniform channel. It is trivial to show that in the case of resistive channels these equations yield noise currents that are inversely proportional to the channel resistance, i.e. to the gate length.

The concept of using an effective temperature of r_{ds} to describe the noise of FET's was used by Pospieszalski [6]. In his work the effective temperature of r_{ds} was one of two fitting parameters used to determine the noise parameters of FET's. In this work, T_{eff} is defined as the temperature of r_{ds} necessary to produce i_{dsn} as given by

$$T_{eff} = \frac{\overline{i_{dsn}^2} r_{ds}}{4k_B} \quad (5)$$

Figure 5 contains the results for the MESFET's and MOD-

FET. Both the long gate MESFET's and the short gate MODFET had T_{eff} which increased with increasing V_{DS}. However, the T_{eff} dependence on I_{DS} was not as well behaved. The T_{eff} of both the 0.5μm MESFET, and the 0.15μm MODFET increased with increasing I_{DS}. The 1.0μm MESFET did not have a simple monotonic behavior. The dependence on V_{DS} suggests that T_{eff} might represent some sort of carrier heating phenomenon. However, the dependence on I_{DS} is not indicative of carrier heating in an obvious way. The main reason for I_{DS} modulation is a variation of the total amount of charge. Thus, no T_{eff} changes should be expected since no obvious carrier heating variations are present. However, it remains to be seen whether variations in transport mechanisms, such as scattering, affected by the presence of larger numbers of carriers could result in the observed noise temperature changes with I_{DS}.

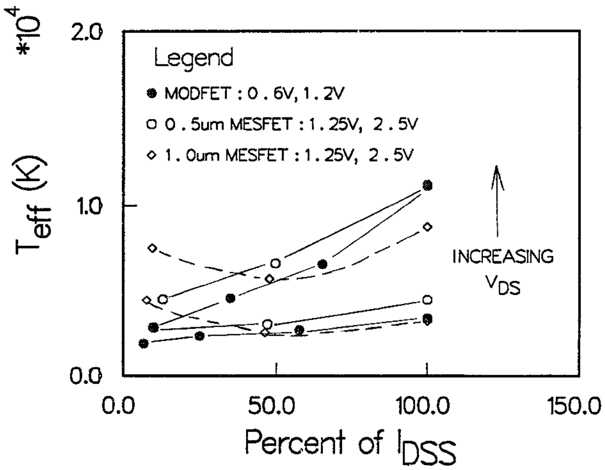

Figure 5: T_{eff} as a function of bias for the long gate MESFET's and the short gate length MODFET.

CONCLUSIONS

The microwave drain noise characteristics have been studied for conventional long (1.0 μm and 0.5 μm) gate GaAs MESFET's and short ($\approx$ 0.15 μm) strained InGaAs/ InAlAs/InP MODFET. The total drain noise of the MODFET was found to be greater than the MESFET's over the entire bias range tested. This contradicts the F_{min} results where the MODFET's had very low noise in comparison. Estimated relative parasitic contributions were found to be far greater for the MODFET noise than the MESFET noise. This is most likely due to the far greater g_m of the MODFET. The estimated intrinsic channel noise was greater for the MODFET structure as well. The MESFET's displayed only an I_{DS} dependence in both the total drain noise and the intrinsic channel noise. In contrast the MODFET had some V_{DS} dependence which was attributed to: (i) short channel effects, and (ii) change in conduction mechanisms due to a low breakdown voltage. Study of an effective temperature concept showed that it does not have any obvious relation to carrier heating.

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References

[1] Folkes, "Thermal Noise Measurements of MESFET's", IEEE Trans. on Microwave Theory and Techniques, Vol. 35, No. 12, Dec., 1987, pp 1208-1217.

[2] M. S. Gupta et al, "Microwave Noise Characterization of GaAs MESFET's: Evaluation by On-Wafer Low-Frequency Output Noise Current Measurement", IEEE Trans. on Microwave Theory and Techniques, Vol. 35, No. 12, Dec., 1987, pp 1208-1217.

[3] R. A. Pucel et al, "Signal and Noise Properties of GaAs Microwave FET", Advan. Electron. Electron Phys., Vol. 38, p. 195, 1975.

[4] B. Carnez et al, "Noise Modeling in Submicrometer-Gate FET's", IEEE Trans. on Electron Devices, Vol. 28, No.7, July, 1981, pp 784-789.

[5] A. Cappy et al, "Noise Modeling in Submicrometer-Gate Two Dimensional Electron-Gas Field-Effect Transistors", IEEE Trans. on Electron Devices, Vol. 32, No.12, Dec., 1985, pp 2787-2796.

[6] M. W. Pospieszalski, "Modeling of Noise Parameters of MESFET's and MODFET's and Their Frequency and Temperature Dependence", IEEE Trans. on Microwave Theory and Techniques, Vol. 37, No.9, Sept., 1989, pp 1340-1350.

[7] A. Cappy, "Noise Modeling and Measurement Techniques", IEEE Trans. on Microwave Theory and Techniques, Vol. 36, No.1, Jan., 1988, pp 1-10.

[8] G. I. Ng et al, "Low-Frequency Noise Characteristics of Lattice-Matched ($x = 0.53$) and Strained ($x < 0.53$) $In_{0.52}Al_{0.48}As/In_xGa_{1-x}As$ HEMT's", IEEE Trans. on Electron Devices, Vol. 39, No. 3, March, 1992, pp 523-532.

[9] V. Adamian et al, "A Novel Procedure for Receiver Noise Characterization", IEEE Trans. on Instrumentation and Measurement, June, 1973, pp 181-182.

[10] I. C. Kizilyalli et al, "Scaling Properties and Short-Channel Effects in Submicrometer AlGaAs/GaAs MODFET's: A Monte Carlo Study", IEEE Trans. on Electron Devices, Vol. 40, No.2, Feb., 1993, pp 234-249.