LOW FREQUENCY NOISE MEASUREMENTS OF GaAs FETs

A.N. Riddle and R.J. Trew

Dept. of Electrical and Computer Engineering, North Carolina State University

Raleigh, NC 27695 (919) 737-2336

ABSTRACT

A knowledge of low frequency noise in FETs is essential in designing oscillators, multipliers, and broadband amplifiers for fiber optics. Measurements on commercial and research GaAs FETs are presented which show up to 25 db differences in the 1/f noise of similarly sized devices. The presence of discrete traps creates even larger differences. The importance of material quality over FET size is demonstrated. Simple equations are presented which describe the noise sources and noise figure of an FET at all frequencies.

INTRODUCTION

A knowledge of the noise characteristics of GaAs FETs is essential for oscillator, multiplier, mixer, A/D converter and roadband fiber optic amplifier design. Equations are presented ι the next section which describe the noise sources and the noise figure of an FET at all frequencies of FET operation. Special attention is paid to low frequency 1/f and trap noise. The last section presents measurements of the low frequency noise in commercial and research GaAs FETs. These measurements show that in many cases material purity is far more important than FET size in determining low frequency noise.

FET NOISE SOURCES

Fig. 1 shows a FET model with noise sources. This model extends that in [1] to include leakage current and low frequency noise sources. The gate leakage current and 1/f noise in the drain current are very important in determining FET noise characteristics below several hundred megahertz. The P,R, and C FET noise coefficients, as introduced by van der Ziel [2], are used here. The following equations describe the equivalent noise sources of the FET in Fig. 2:

$$\overline{e_u^2}/Hz = 2qI_{lkg}\frac{1+(\omega C_{gs}R_i)^2}{\omega^2 C_{gs}^2}\left[\frac{K_b}{K_a(1+a)}\right]^2 + 4kT(R_m+R_f) + \frac{4kTP}{g_m}\,\frac{1+(\omega C_{gs}R_i)^2}{(1+a)^2}\left(a^2+\frac{R(1-C^2)(1+2a)}{K_a}\right), \quad (1)$$

$$\overline{i_n^2}/Hz = 4kT\,\frac{\omega^2 C_{gs}^2 K_a}{g_m}\,(1+a)\,, \quad (2)$$

$$Z_c = R_f + R_m + \frac{K_b}{K_a(1+a)}\,\frac{1+j\omega C_{gs}R_i}{j\omega C_{gs}}, \quad (3)$$

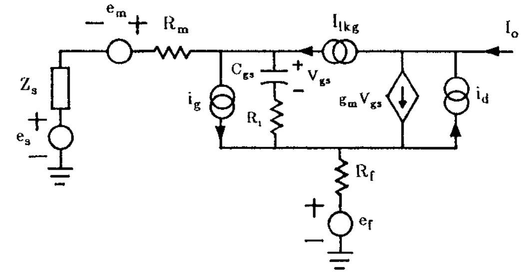

Figure 1. FET noise model with 1/f noise in i_d and leakage current I_{lkg}.

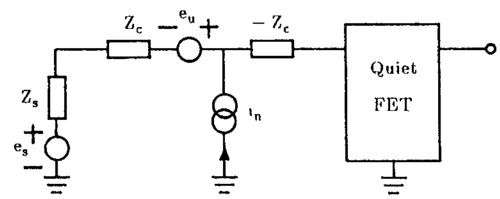

Figure 2. Equivalent noise sources of an FET using a correlation impedance.

where

$$K_a = P + R - 2C(PR)^{0.5}\,,\quad K_b = P - C(PR)^{0.5}\,,$$

$$a = \frac{qI_{lkg}\,g_m}{2kT\omega^2 C_{gs}^2 K_a}\,,\quad P = \frac{\overline{i_d^2}/Hz}{4kTg_m}\,,$$

$$R = \frac{g_m}{4kT\omega^2 C_{gs}^2}\,\overline{i_g^2}/Hz\,,\quad C = -j\,\frac{\overline{i_d i_g^*}}{\left(\overline{i_d^2}\;\overline{i_g^2}\right)^{0.5}}\,, \text{ and}$$

$$Z_c = R_c + jX_c\,.$$

The use of a correlation impedance is discussed in [3]. The P term contains 1/f noise and will be discussed in detail later. The R, C, and high frequency portion of the P term are best calculated by a FET analysis program [4]. The above equations lead to the noise figure equations below:

$$F_{\min} = 1 + 2\, g_n \,(R_c + R_{opt}) \ \text{,or}$$

$$F_{\min} \approx 1 + \frac{2\omega C_{gs}}{g_m}\left[K_a g_m (1+a)\left(R_m + R_f + \frac{P}{g_m}\left\{\frac{a}{1+a}\right\}^2\right)\right]^{0.5} + \frac{2\omega^2 C_{gs}^2 K_a}{g_m}\left(R_m + R_f + \frac{K_b}{K_a\,(1+a)}\,R_i\right) , \qquad (4)$$

$$F = F_{\min} + \frac{g_n}{R_s}\left[(R_s - R_{opt})^2 + (X_s - X_{opt})^2\right] , \qquad (5)$$

where

$$R_{opt} = \left(R_c^2 + \frac{r_u}{g_n}\right)^{0.5} , \quad X_{opt} = -\,X_c \ ,$$

$$r_u = \overline{e_u^2}/Hz\ /4kT \ \text{,and} \quad g_n = \overline{i_n^2}/Hz\ /4kT \ .$$

I_{lkg} is the gate leakage current of the FET. The P coefficient is split into two terms for this analysis, so

$$P = P' + P'' \ ,$$

where P' is calculated from a high frequency FET modeling program and P" is a measured quantity including 1/f and trap noise. For qualitative purposes, $P = P'(1+f_c/f)$ can be used. However, the differing slopes of the noise spectrum and presence of traps make the idea of a 1/f noise corner unsuitable for accurate device comparisons.

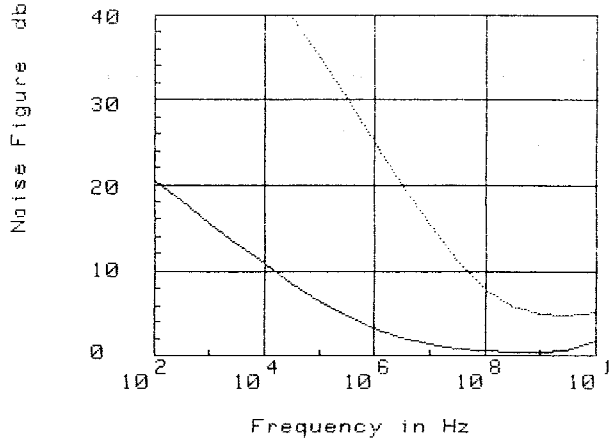

Figure 3. GaAs FET (.5x250μ) minimum noise figure (___) and noise figure with a 50 Ω source resistance (...).

Fig. 3 shows the minimum noise figure (solid line) of a typical 0.5x250μ GaAs FET. Note the $f^{-0.5}$ slope at low frequencies which comes from the square root factor in (4). If the FET is driven from a 50 ohm source, the dotted line in Fig. 3 is the resulting noise figure. Note the 1/f slope of the dotted line at low frequencies. The FET used for this example had $R_f = R_m = 2.5\Omega$, $R_i = 1\Omega$, $g_m = 0.02$ *mhos*, $C_{gs} = 0.2pF$, $I_{lkg} = 1\mu A$, P=1.8, R=0.2, C=0.98, and $f_c = 170MHz$. Fig. 4 shows the minimum noise figure (solid line) and the noise

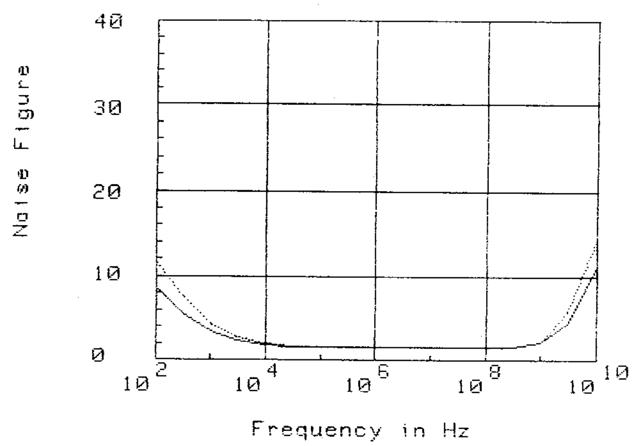

Figure 4. Silicon bipolar transistor (9GHz f_T) minimum noise figure (___) and noise figure with a 50 Ω source resistance (...).

figure in a 50Ω system of a 9GHz f_T bipolar transistor. A comparison of Figs. 3 and 4 emphasizes the noise problems of GaAs FETs at low frequencies.

A 1/f noise spectrum in MESFETs can be caused by an approximately continuous distribution of traps in space and energy, or by bulk 1/f noise as described by Hooge [5]. Discrete trapping centers in the depleted region of a FET channel have been shown to create a noise spectrum shaped like a low-pass filter [6]. Recently, a thorough investigation of MESFET low frequency noise demonstrated that the noise originated in the depletion region underneath the gate, or at the channel-substrate interface [7]. Earlier work showed similar results but concluded that because 1/f noise is essentially independent of bias the sources were distributed uniformly through the channel and interacted mainly with the gate depletion region [5]. The positional dependence of the time constants of those traps in the transition region from the depletion region to the channel were used to explain the 1/f noise spectrum [5].

Although there is still a lot of debate on the cause of 1/f noise in MESFETs, there is general agreement that the gate voltage noise has a spectral density given roughly by:

$$S_e(f) = \overline{e_n^2}/Hz = \frac{K_f\,(0.5)^{m-1}}{Z L^m f^{\iota}} \qquad (6)$$

where Z = the FET gate width, L = the FET gate length, and m = 2 if L < 0.5 μm and 1 if L > 0.5 μm [7]. The dependence of 1/f noise on gate length changes for FETs with gate lengths less than 0.5 μm because of the increasing influence of the v_{sat} region on device operation [7].

The existence of discrete traps in MESFETs can make it difficult to calculate a slope (ι) for 1/f noise. The total low frequency noise includes 1/f noise and traps, so P may be written as:

$$P = P'\left(1 + \frac{f_c^{\iota}}{f^{\iota}}\right) + \sum_{i=1}^{\infty} \frac{P_i}{1+\omega^2\tau_i^2} \ . \qquad (7)$$

The P_i coefficients vary with temperature and trap density [6]. 1/f noise has been measured to as low as 0.01 Hz in GaAs FETs [8].

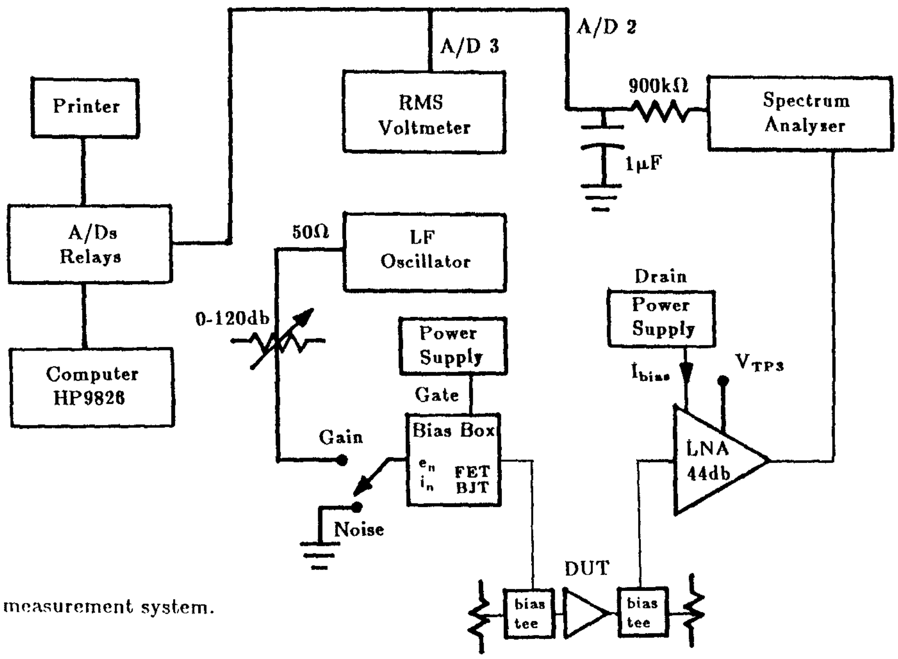

Figure 5. Low frequency noise measurement system.

Table I MESFET Noise Characteristics									
Device	I_{DSS} mA	L μ	Z μ	V_{DS}	V_{GS}	I_{DS} mA	I_{lkg} μA	e_n (μV/ √Hz) 1kHz	ι
AT106-3#1	28	0.5	250	2.5	-1.3	5	1.2	1.2	1.28
	28	0.5	250	3.0	-1.3	5	1.7	1.6	1.26
	28	0.5	250	3.0	-1.1	10	1.1	1.5	1.26
	28	0.5	250	3.5	-1.25	5	2.7	1.8	1.22
AT106-3#2	43	0.5	250	3.0	-1.2	5	3.5	1.6	1.31
AT106-5#1	40	0.5	250	3.1	-0.47	10	0.072	0.255	1.03
AT12570#1	111	0.5	500	2.6	-1.5	10		0.85	1.29
AT12570#2	102	0.5	500	2.6	-1.3	10		0.9	1.35
MGF1200	64	1.0	450	3.0	-1.9	5	0.001	0.17	1.16
MGF1400	30	1.0	300	3.0	-0.75	3	0.025	0.16	1.08
MGF1402#1	46	0.8	400	2.6	-0.6	5	0.03	0.11	1.02
MGF1402#2	64	0.8	400	2.6	-0.85	7	0.022	0.13	0.96
	64	0.8	400	2.6	-0.7	14		0.13	0.94
MGF1404#2	51	0.3	300	2.6	-0.8	5	0.011	0.13	0.63
	51	0.3	300	2.6	-0.55	15	0.007	0.12	0.6
	51	0.3	300	4.0	-0.9	5	0.04	0.2	0.65
MGF1801#1	240	1.0	800	3.1	-1.96	10	0.066	0.136	0.98
	240	1.0	800	3.1	-1.71	25	0.055	0.106	0.86
HPTC3#2	88	1.0	500	2.6	-1.8	9		0.48	1.06
HPTC3#3	92	1.0	500	2.6	-1.9	9	0.19	0.45	0.9
HPCL	62	1.0	500	2.6	-2.1	6	0.63	0.61	0.95
	62	1.0	500	4.0	-2.4	6	2.3	0.64	0.95
NE710#1	41	0.25	260	4.0	-0.6	5	0.46	0.33	1.1
DXL1503#1	43	0.5	280	3.1	-0.7	10	0.14	0.131	0.8
DXL1503#2	36	0.5	280	3.1	-0.56	10	0.09	0.114	0.79
DXL0503#1	38	0.3	280	3.1	-0.68	10	4.34	0.296	0.93
DXL0503#2	46	0.3	280	3.1	-0.77	10	2.36	0.258	0,9
DXL3504#1	84	0.5	280	3.1	-3.35	10	0.27	1.006	1.06
DXL3504#2	94	0.5	280	3.1	-3.92	10	0.39	2.106	1.1
FSC11#1	59	0.5	400	3.1	-0.69	10	0.17	0.124	0.84
FSC11#2	62	0.5	400	3.1	-0.88	10	0.41	0.136	0.8
FSC11#3	58	0.5	400	3.1	-0.67	10	0.2	0.135	0.81
	58	0.5	400	4.0	-0.6	16	0.53	0.133	0.76
	58	0.5	400	1.0	-0.71	6	0.004	0.103	0.78
	58	0.5	400	3.1	-0.34	27	0.04	0.107	0.73
	58	0.5	400	3.1	-0.85	4	0.25	0.148	0.84

FET NOISE MEASUREMENTS

Fig. 5 shows the low frequency noise measurement system used to record the data in Table I. The FETs were measured in a high frequency test fixture and terminated in 50Ωs at high frequencies to prevent oscillations. First, the signal generator, computer, and spectrum analyzer were used to measure the gain of the system with low and high input impedances. Next, the computer and spectrum analyzer were used to measure the noise with low and high impedance input terminations. The computer was used to correct the data for noise bandwidth and system gain.

Although most of the FETs had 1/f noise slopes around unity, slopes (ι) varied from 0.6 to 1.3. Trap noise was observed in many of the devices and had considerable influence on the average slope of the noise between 500Hz and 1MHz. In general, the noise was relatively insensitive to gate bias. The noise did show some sensitivity to drain bias and leakage current. The multiple entries of some devices in the table illustrate the relative sensitivities to gate and drain bias. Although the gate leakage current increased with drain bias, and several of the noisier FETs had relatively high leakage currents, no direct correlation could be drawn because there were exceptions (the MGF1404#2).

Figures 6 and 7 show the low frequency noise versus frequency for several GaAs FETs (-180db gives e_n = 1nV per root Hertz). Note that Figure 6 is scaled 10 db higher than Figure 7. While it can be said that within a given manufacturing process the 1/f noise usually decreases as the size of the device increases, as predicted by (6), this comparison can obviously not be made between manufacturers or between processes. The quietest FETs tested were the MGF1404s, MGF1402s, MGF1801s, DXL1503s, and the FSC11LFs. Mitsubishi uses a recessed - gate, VPE process with a buffer layer. The MGF1404#2 had the lowest K_f of any FET measured (0.77×10^{-9}).

If we calculate the value of K_f in (6) for various FETs, we have a measure of 1/f noise that is independent of device size. The FETs in Fig. 6 all had a K_f, at 1kHz, of approximately 2×10^{-7} (L and Z in μm). The FETs of Fig. 7 had K_fs around 2×10^{-9} at 1kHz. Since the devices in Fig. 6 are American, and the devices in Fig. 7 are Japanese it would appear that the GaAs in the active layers of Japanese FETs has fewer trapping centers. Fewer trapping centers may be the result of greater purity in the original material, fewer contaminants during processing, and/or buffer layers [7].

CONCLUSION

Based on Figs. 6 and 7 and Eqn. 6, a difference of 25db can exist in the 1/f noise of similarly sized FETs. From (6), a 0.25x25μ FET would have to be replaced by a 1x500μ FET to give a similar noise reduction. These large differences in 1/f noise levels make material purity and/or buffer layers much more important than FET size for presently available devices.

The noise equations presented here are important because they accurately predict the noise figure of an FET at all frequencies. This knowledge is essential for oscillator and broadband fiber optic amplifier design.

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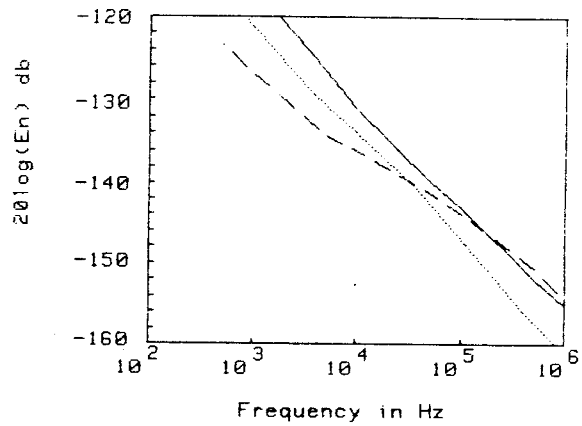

Figure 6. Low frequency noise in an AT10650-3 (___), an AT12570-5 (...), and an HPTC300 (_ _).

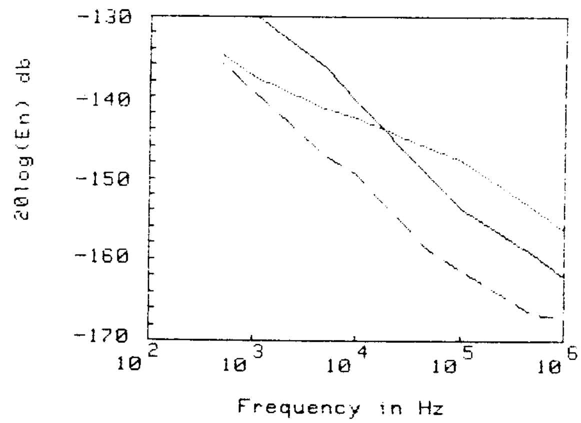

Figure 7. Low frequency noise in an NE71083 (___), an MGF1404 (...), and an MGF1402 (_ _).

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