TEMPERATURE DEPENDENT FUNCTIONAL SMALL-SIGNAL AND NOISE MODEL OF GaAs FET

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ABSTRACT

A new CAD oriented noise model of the GaAs small signal FET is proposed. It introduces only one parameter to describe noise properties of the MESFET, contrary to previous models [1-4], which used more numbers. Model components are bias and temperature dependent. Temperature dependence of parameters is modelled by a numerical approximation to the physical behavior of carrier mobility and carrier saturation velocity in GaAs. Comparison with measured and published transistor parameters is presented.

INTRODUCTION

Existing linear microwave FET models implemented in popular CAD packages make it difficult to predict the effects of bias or temperature changes on the performance of transistor and usually require a set of coefficients to be supplied or measured [2,10,11].
The goal of this work was to develop a simple model, which would require only a limited number of parameters to be identified and would provide sufficient accuracy to be used in the design of microwave devices, especially low noise amplifiers.

MODEL OF THE INTRINSIC FET

Two FET channel regions are considered [5,8]: constant carrier mobility region and saturated velocity region. The assumption was made, that the noise in the first region is of purely thermal origin, and may be represented by the equivalent voltage source e_{nc}, dependent on the channel temperature T (Fig. 1). In the saturated region two main noise sources are accounted for, both dependent on the DC drain current I_D. These are: the high-field diffusion noise [1,6] and the current distribution between channel and substrate.

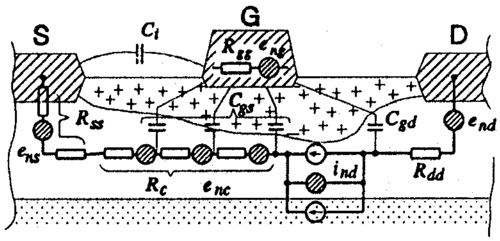

Fig. 1. Noise sources in the microwave FET.

Substrate current may reach 20 - 40 % of the total drain current [6], and the scattering mechanism is random. These noise processes in the channel second region have been modelled as one current noise source i_{nd}, with the mean square value linearly dependent on the I_D value. Noise sources: e_{nc} and i_{nd} are not correlated. Proposed model of the microwave FET [5] is shown below.

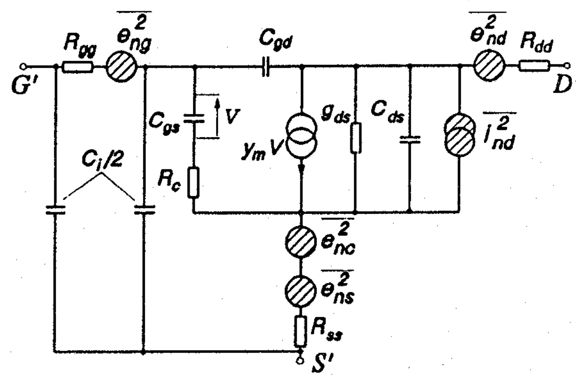

Fig. 2. Noise model of the intrinsic FET

The placement of the source e_{nc} reflects the reasoning, that the origin of this noise is most of the area under the gate. The exact model of the gate-channel region should be that of a distributed RC line, but the author follows the suggestions by P. Ladbrooke [6], that good lumped representation is obtained, when channel resis-

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tance R_c is placed in series with the channel-gate capacitance C_{gs}.
The mean RMS values of the main noise sources are

$$\overline{e_{nc}^2} = 4kTR_c df \tag{1a}$$
$$\overline{i_{nd}^2} = C_n \cdot qI_D df \tag{1b}$$

The value of the dimensionless coefficient C_n is found in the process of fitting the model to the experimental data. Thermal noise in other portions of the chip is represented by the sources e_{ng}, e_{ns} and e_{nd}, where

$$\begin{aligned} \overline{e_{ng}^2} &= 4kTR_{gg} df \\ \overline{e_{ns}^2} &= 4kTR_{ss} df \\ \overline{e_{nd}^2} &= 4kTR_{dd} df \end{aligned} \tag{2}$$

T is the channel temperature which depends on actual bias (I_D and V_{DS}) and on ambient temperature T_{amb}. Several components in the model are bias dependent. The model was created with iterative computations in the CAD routines in mind, and simple, albeit less accurate approach was considered.
Following relationships were established to model the dependence on the drain current

$$y_m = g_m e^{-j\omega\tau} \quad g_m = g_{mo} \cdot f(x) \quad g_{ds} = g_{do} \cdot f(x) \tag{3}$$

$$R_c = R_{co} \cdot \frac{c+1}{c+x^2} \qquad C_{gs} = C_{gso} \cdot \left(\frac{d}{e-x^2}\right) \tag{4}$$

g_{mo}, g_{do}, R_{co}, C_{gso} are the values of particular parameters for $I_D = I_{dss}$. Parameter x and the function $f(x)$ are defined as follows

$$x = \left(\frac{I_D}{I_{dss}}\right) \qquad f(x) = \frac{(1+a+b)x^2}{x^2+ax+b} \tag{5}$$

Coefficients a and b in (5) are chosen to model a typical behavior of transconductance g_m versus drain current. It was found, that values: $a = 0.05$ and $b = 0.02$ give very good fit for many different transistors evaluated. Typical values of other coefficients are: $c = 0.6$, $d = 2$, $e = 3$. The dependence on drain voltage V_{DS} was also modelled, but it was restricted to two elements only: g_{ds} and C_{gd}. Following approximation was found satisfactory for small deviations from a typical value of $V_{DS} = 3$ V

$$\begin{aligned} g_{ds}(V_{DS}) &= g_{ds3} \cdot \left(\frac{3.6}{V_{DS}+0.6}\right) \\ C_{gd}(V_{DS}) &= C_{gd3} \cdot \left(\frac{8}{V_{DS}+5}\right) \end{aligned} \tag{6}$$

where g_{ds3}, C_{gd3} are the values at $V_{DS} = 3$V.

TEMPERATURE DEPENDENCE OF THE MODEL PARAMETERS

Elements of the model depicted in Fig. 2 reflect the physical processes taking place in the FET structure and are linked with such physical quantities, as transistor dimensions and with parameters of the manufacturing process. In this work, simple expressions relating model parameters to the FET geometry and the GaAs properties, were adopted [6,7].

$$\begin{aligned} &R_c \approx \frac{v_{sat}}{\mu_o} \cdot L_g f(I_D) && C_{gs} \approx \frac{\varepsilon N W_g}{d}\left(1 + \frac{L_x}{2L_g}\right) \\ &g_m \approx \frac{\varepsilon v_{sat} W_g}{d} \cdot \varphi(h-d) && C_{gd} \approx \frac{2\varepsilon W_g}{1 + \frac{2L_g}{L_x}} \\ &R_{gg} \approx \frac{\rho W_g}{3tL_g} && R_{ss} \approx \frac{L_{sg}}{qN\mu_o h W_g} + R_m \end{aligned} \tag{7}$$

where R_m - contact resistance, and the GaAs parameters are: v_{sat} and μ_o - electron saturation velocity and mobility, $\varepsilon = 12.85$, N - the donor doping density and ρ - the resistivity of the gate metal. The dimensions L_{sg}, L_g, L_x, h, d and t are explained in Fig. 3.

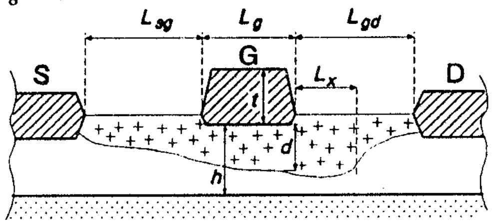

Fig. 3. Cross-section of the GaAs FET.

The function $\varphi(h - d)$ may be selected to provide proper g_m variation with I_D, as in (3). Depleted region thickness d at the end of the channel is related to the drain current I_D by

$$I_D = qNv_{sat}(h - d)W_g \tag{8}$$

The zero gate bias current I_{dss} varies with temperature in proportion to v_{sat}. Usually transistors in amplifiers are operated at constant drain current and the parameter $x(T)$ /see (5)/ is equal

$$x(T) = \frac{I_D}{I_{dss}(T)} = \frac{h-d}{h-d_o} \tag{9}$$

where $d_o = d(V_{GS} = 0)$. The ratio $d(T)/d_{300}$

$$\frac{d(T)}{d_{300}} = \frac{1 - x(T) \cdot (1-K)}{1 - x_{300} \cdot (1-K)} \tag{10}$$

where $K = d_o/h$ /typically $K \approx 0,6 \div 0,8$/

is needed for evaluation of the C_{gs} variation with temperature. Final equations for the model parameters at temperature T are as follows

$$g_{mo} = g_{mo300}\frac{v_{sat}(T)}{v_{300}} \qquad g_m(T) = g_{mo}(T)\cdot f(x(T))$$

$$R_c(T) = R_{c300}\frac{v_{sat}(T)}{v_{300}}\cdot\frac{\mu_{o300}}{\mu_o(T)} \qquad C_{gs}(T) = C_{gs300}\frac{d_{300}}{d(T)} \qquad (11)$$

$$C_{gd}(T) \approx const \qquad \tau(T) = \tau_{300}\cdot\frac{v_{300}}{v_{sat}(T)}$$

Numerical model of temperature variation of μ and v_{sat} is based on typical data [7] for donor doping densities encountered in microwave FETs (Fig. 4 and 5).

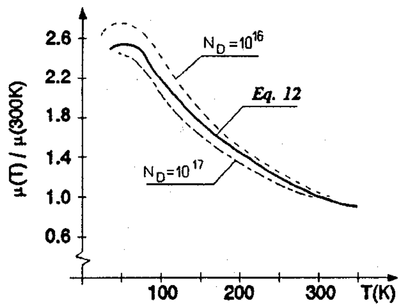

Fig. 4. The dependence of mobility μ_o on temperature.

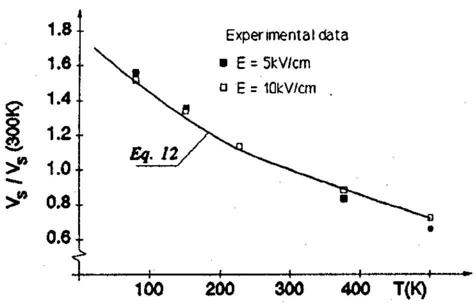

Fig. 5. The dependence of saturation velocity on T.

The approximation of physical data is given by equations (12)

$$\mu(T) = \mu_{300}\cdot\frac{7.115\,(0.4 + y^2)}{(1 + x)\cdot(1 + y^2)}$$

$$v_{sat}(T) = v_{300}\cdot\left(\frac{2090}{T + 1790}\right)^{3.568} \qquad (12)$$

where μ_{300} and v_{300} are the values for T = 300 K, and parameter y = T[K]/50.

SELECTED RESULTS

Equations (11) were implemented in the computer program for transistor modelling. Data for several transistors types were compared with computed results and good agreement was obtained. The plot of minimum noise figure F_{opt} in Fig. 6 shows the temperature dependence which agrees well with the results published (e.g. [10]). It has been confirmed, that F_{opt} is relatively insensitive to drain current variations at *low* temperatures, but strongly dependent on I_D at high temperatures. Data in Table 1 confirms the usefulness of the model proposed and Fig. 7. shows the close model fit for different values of drain current.

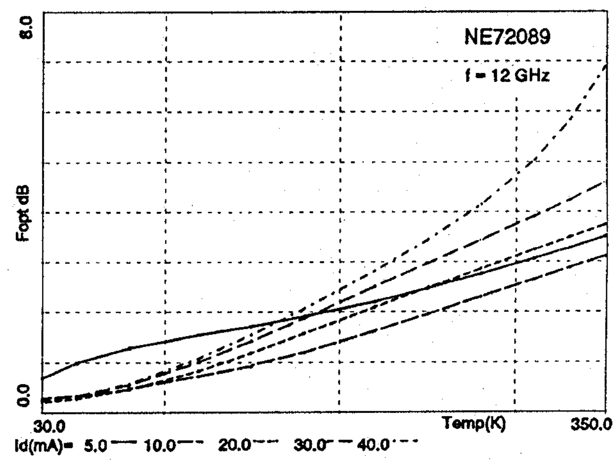

Fig. 6. F_{opt} versus temperature and drain current.

Table 1 Computed vs published noise parameters for the FSC10FA transistor [9]

f=8.4 GHz Ambient temperature = 297 K				
I_D		T_{nmin}[K]	R_{sopt}[Ω]	X_{sopt}[Ω]
5	published	-	-	-
mA	computed	111	15.9	28.9
10	published	135	11.1	29.0
mA	computed	134	13.5	25.5
15	published	131	12.5	28.0
mA	computed	155	12.4	22.1

Ambient temperature = 12.5 K				
I_D		T_{nmin}[K]	R_{sopt}[Ω]	X_{sopt}[Ω]
5	published	16	1.8	29
mA	computed	16.4	5.6	31.3
10	published	14	4.1	28
mA	computed	14.1	5.8	32.0
15	published	16	4.9	26
mA	computed	14.2	5.1	34.2

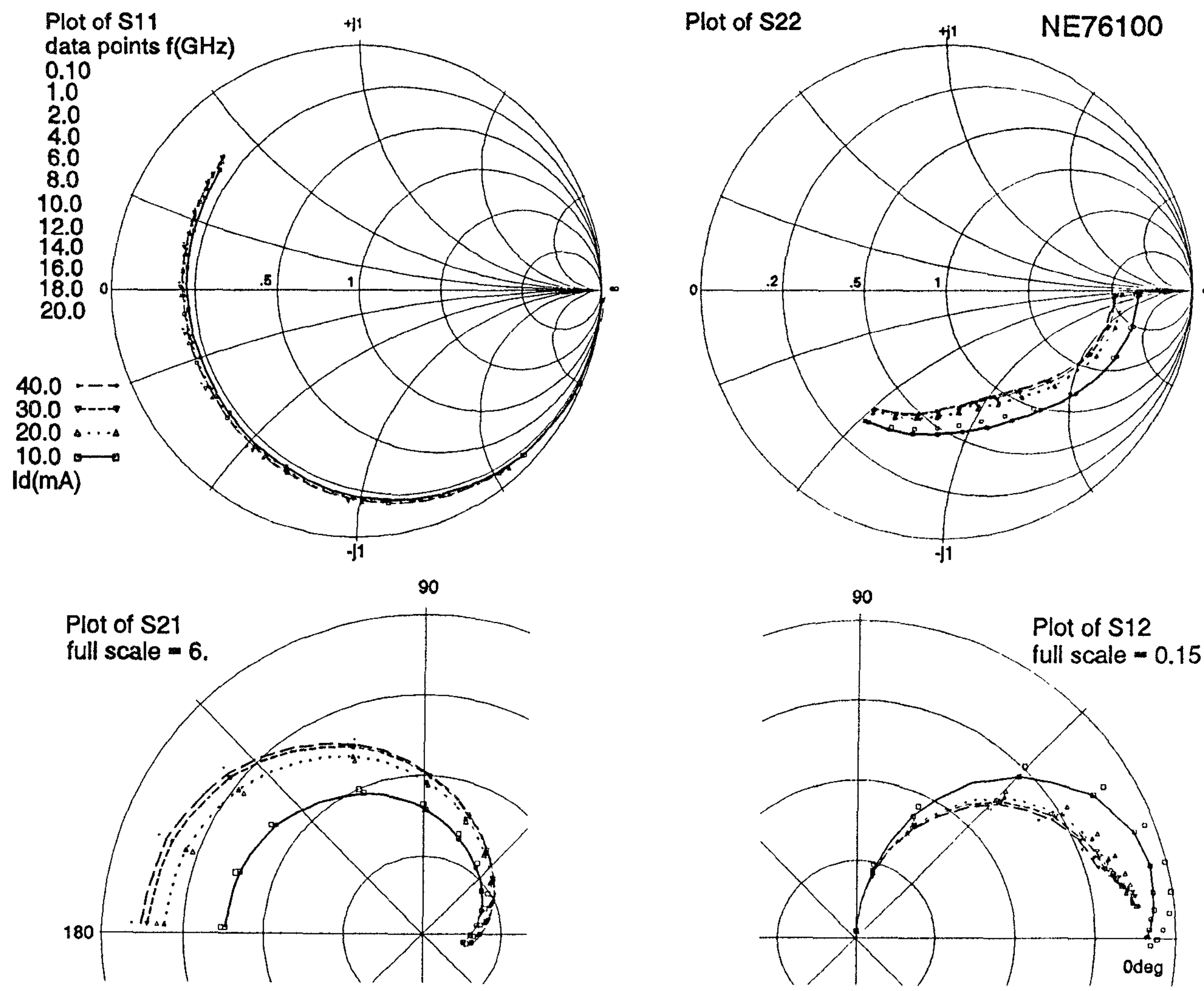

Fig. 7. Modelled and measured *S*-parameters of the NE76100 transistor vs frequency for different drain currents.

REFERENCES

[1] H. Fukui, "Design of Microwave GaAs MESFET's for Broad-Band Low-Noise Amplifiers", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 643-650, July 1979.

[2] R.S.Pengelly et al., "Transistor Model Predicts Effects of Temperature", *Microwaves & RF*, no. 7, pp.117-122, July 1989.

[3] M.W. Pospieszalski, "A New Approach to Modeling of Noise Parameters of FET's and MODFET's and Their Frequency and Temperature Dependence", *Electronics Division Internal Report No. 279*, NRAO, Charlottesville, VA, July 1988.

[4] M.W.Pospieszalski, A.C.Niedzwiedzki, "FET Noise Model and On-Wafer Measurements of Noise Parameters", *1991 MTT-S Digest*, pp. 1117-1120.

[5] Z. Nosal, "Single Parameter Noise Model of MESFET", *Proc. 15-th Conf. Circuit Theory and Electr. Circuits*, pp. 472-477, Szczyrk 1992, Poland.

[6] P.H. Ladbrooke, "*MMIC Design GaAs FETs and HEMTs*", Artech House, 1989.

[7] M. Shur, "*GaAs Devices and Circuits*", Plenum Press, New York and London, 1987.

[8] J. Portilla et al., "An Improved CAD Oriented FET Model for Large-Signal and Noise Applications", *1994 IEEE MMT-S Digest*, pp. 849-852.

[9] M.W. Pospieszalski, "Low-Noise, 8.0-8.8 GHz, Cooled GASFET Amplifier", *Electronics Division Internal Report No. 254*, NRAO, Charlottesville, VA, December 1984.

[10] H. Meschede et al., "RF Investigations on HEMTs at Cryogenic Temperatures down To 20 K Using an On-wafer Microwave Measurements Setup", *Proc. 22 Eur. Micr. Conf.*, Helsinki, 1992, pp. 151-155.

[11] S. Lardizabal et al., "Experimental Investigation of the Temperature Dependence of PHEMT Noise Parameters", *1994 IEEE MTT-S Digest*, pp. 845-848.