Temperature and Dispersion Effect Extentions of Chalmers Nonlinear HEMT and MESFET Model

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ABSTRACT
Temperature and dispersion effects have been investigated and included in the Chalmers nonlinear model for HEMTs and MESFETs. DC, pulsed DC, low frequency (10Hz-10MHz), RF and small signal S-parameter measurements (1-18GHz) have been made on a large number of HEMT and MESFET devices from different manufacturers in the temperature range 17-400K in order to evaluate the model.

INTRODUCTION

Nonlinear simulations are a useful tool for active circuit design . The accuracy of the simulation depends on how well the model describes the performance of the transistor. In some applications dispersion and temperature effects are important to take into account [1-6]. The presence of traps in MESFETs and HEMTs causes difficulty in modelling their dynamic behaviour. Low frequency dispersion phenomena are observed for the model parameters, where parameter values are different at DC and microwave frequencies [1-5]. Temperature effects are of primary importance in power devices, but can be observed in some low power MMICs and naturally in devices, which have to operate in large temperature intervals [6].This paper is extending the Chalmers nonlinear model for HEMTs and MESFETs with the ability to model these effects.

THE MODEL

The equation for the drain current of the Chalmers model is:

$$I_{ds} = I_{pk}(1+\tanh(\Psi))(1+\lambda V_{ds})\tanh(\alpha V_{ds}) \quad (1)$$

where I_{pk} and V_{pk} are the current, respectively the gate voltage, at which the maximum of the transconductance occurs, l is the channel length modulation parameter and a is the saturation voltage parameter [7].

Parameters of the drain part, α and λ, are the same as those used in the modified Materka model [8]. Y is in general a power series function centred at V_{pk} and with a variable V_{gs}, i.e.:

$$\psi = P_1(V_{gs}-V_{pk}) + P_2(V_{gs}-V_{pk})^2 + P_3(V_{gs}-V_{pk})^3 \ldots \quad (2)$$

As a first approach we choose P_1 as $P_{1s}=g_{ms}/I_{pks}$, where g_{ms} and I_{pks} are measured in the saturated current region. When the device is operating in the saturated region , then P_1 and V_{pk} can be considered constant. If a high accuracy at low drain and negative voltages is important, then the drain voltage dependence of P_1 and V_{pk} should be taken into account or the values of P_1 and V_{pk} should be extracted from data measured at the working bias point. In our model we use the following expressions for V_{pk} and P_1 which describe global behaviour of the transistor [9]:

$$V_{pk}(V_{ds}) = V_{pk0} + (V_{pks} - V_{pk0})(1+\lambda V_{ds})\tanh(\alpha V_{ds}) \quad (3)$$

$$P_1 = P_{1s}[1 + (\frac{P_{10}}{P_{1s}} - 1)\frac{1}{\cosh^2(BV_{ds})}] \quad (4)$$

where V_{pk0} and V_{pks}, are V_{pk} measured at V_{ds} close to zero and in the saturated region, respectively, $P_{10}=g_{mo}/I_{pko}$ at V_{ds} close to zero and B is a fitting parameter ($B\approx1.5\alpha$). In many cases $(1+\lambda V_{ds})\approx1$.

MEASUREMENT SET-UP

DC- and S-parameters of the packaged devices were measured in a Maury MT-950 transistor fixture and in a specially developed microstrip fixture that we found to be suitable in the temperature interval 17-400K. HP4195A VNA was used to measure low frequency S-parameters (10Hz-500MHz) of the transistors and Wiltron 360/HP 8510 C VNA were used for measurements in the frequency range 0.1-18 GHz. Values of the output resistances were extracted directly from HP4195A data. We used the equivalent circuit of the transistor shown in Fig. 1 to model the packaged transistors. The parasitic parameters L_g, L_d, L_s, C_p etc. were fixed at the values extracted from the S-parameter measurement at V_{ds}=0 V at room temperature. R_g, R_d, R_s were extracted from DC [11] and cold FET S-parameter measurements as a function of the temperature. The component values of the cold FET small signal equivalent circuit were extracted by using our own extraction program, but similar results were obtained using MDS (Hewlett-Packard), Scout and Microwave Harmonica (Compact Software). The frequency dispersion of trans-conductance and output conductance of the device [1-5] was investigated. For this purpose pulsed DC, low frequency RF (10Hz-10MHz) and S-parameter measurements were performed. Block diagram of the pulsed and RF set up is shown in Fig. 2.

DISPERSION MEASUREMENTS

The main idea of pulsed DC and RF measurements was to study the dispersion of the transconductance and temperature effects. The easiest way to monitor the dispersion of g_m was to use resistors with small resistance values (R_{d1}=2 Ω, R_{d2}=0 Ω) which was acting as a current probe. Then the gain of the circuit A_v is given by:

$$A_v = g_m R_{ds} R_{d1} / (R_{ds} + R_{d1}) \approx g_m R_{ds} \quad (5)$$

and the dispersion of the output conductance is not influencing the accuracy of the g_m measurement.

Temperature effects were studied using larger values of the resistances (R_{d2}=47 Ω, R_{d1}=10 Ω) in order to avoid instabilities and to decouple the transistor from the measuring equipment. The measured difference between DC transconductance and transconductance values extracted from pulsed DC, RF and S-parameters was very small for the most new HEMT devices. For some old MESFET devices dispersion effects were quite noticeable, for example MGF1404 (MGF14), Fig 3b.

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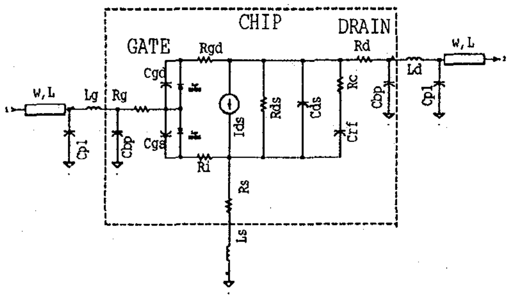

Fig. 1. Equivalent circuit of the HEMT.

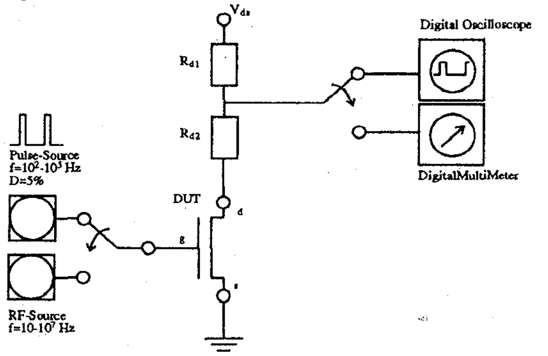

Fig. 2. Block diagram of dispersion measurement set-up.

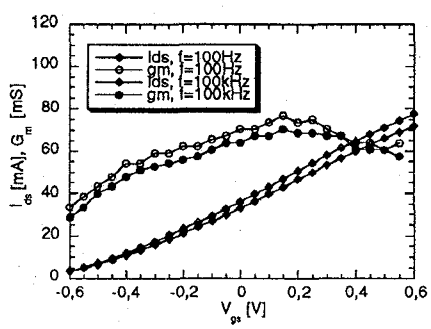

Fig 3a. Dispersion for MGF1404 from pulsed measurements.

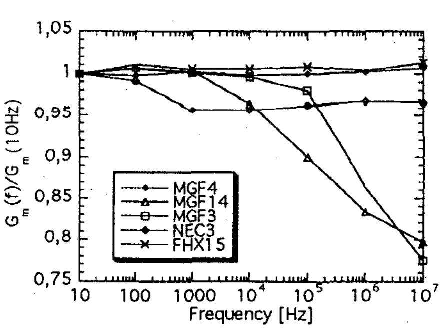

Fig. 3b. $g_{mpk}(f)$ from RF measurements.

An RC-series circuit was used to model low frequency dispersion of the output conductance and by adjusting the λ values extracted from DC measurement and the values of RC-circuit it was possible to fit both DC characteristics and S-parameters. A junction model, which is available in the FET model of MDS (HP), was used to model the forward conduction characteristic of the HEMT Schottky diode. DC-parameters were measured by using a HP 4145B parameter analyser. Large signal model parameters were extracted for packaged HEMTs and MESFETs manufactured by different manufacturers. The values of I_{pk}, P_{1s}, P_{10}, V_{pk0}, V_{pks}, α and λ have been determined from DC and pulsed DC measurements. The process of the extraction of the model parameters is described in greather detail in [10]. The extracted model parameters for some HEMT and MESFET devices[1] were used in Harmonic Balance Simulator (MDS from HP) to simulate the DC and microwave performance of those transistors. In Fig. 3a and b measured frequency dependence of I_{ds} and g_m are presented, extracted from DC, pulsed and RF measurements. When dispersion effects are significant they can be taken into account as follows:

$$P_1 = P_{1d}P_{1s}[1+(\frac{P_{10}}{P_{1s}}-1)\frac{1}{\cosh^2(BV_{ds})}] \qquad (6)$$

$$P_{1d} = \frac{P_{1srf}}{P_{1sdc}} + \frac{P_{1sdc}-P_{1srf}}{P_{1sdc}}\frac{1}{1+\left(f/f_{tr}\right)^2} \qquad (7)$$

It is also possible to use some smoother type of frequency dependence:

$$P_{1d} = \frac{P_{1srf}}{P_{1sdc}} + \frac{P_{1sdc}-P_{1srf}}{P_{1sdc}}\frac{1}{\cosh\left(f/f_{tr}\right)^2} \qquad (8)$$

where P_{1d} is the coefficient responsible for the frequency dispersion, P_{1sdc} is the P_{1s} measured at DC for saturation drain voltages, P_{1srf} is extracted from RF measurements and f_{tr} is the corner frequency for the dispersion effects.

CRYOGENIC MEASUREMENTS

The main parameters of the model: V_{pk0}, V_{pks}, g_m, I_{pk}, P_1, P_{10}, λ, C_{gs}, C_{gd}, are also dependent on the temperature. Measured dependencies for different HEMT and MESFET devices in the temperature range from 17-400K are presented in Fig. 4-10. The voltages at which we have maximum transconductance, V_{pk0} and V_{pks}, are linearly increasing at low temperature, Fig. 4. P_{1s} is almost constant with temperature, Fig. 7a, because of a nearly monotonic increase of both g_m and I_{pk} at low temperature, Fig. 5b. The changes of the transconductance are due mainly to the increase of I_{pks} at cryogenic temperature. The largest change we have monitored is the increase of the coefficient P_{10} at cryogenic temperatures, Fig. 7b. This feature is very important for the circuits that are operated at low drain voltages, like modulators, resistive mixers, etc. It means that it will be possible to reduce the power needed from the local oscillator for full drive of a resistive mixer. Slight increases of λ, Fig. 8, and α for all the transistors are monitored at low temperatures. Forward gate bias voltage at fixed gate current, Fig. 9, is increasing at cryogenic temperatures. These changes are almost linear in the temperature range 200-400K, at lower temperatures the increase in V_{gs} is not as linear [12].

[1]NEC32684 (NEC), FHX15FA (Fujitsu), MGF4317D, MGF1404 and, MGF1303B (Mitsubishi) named NEC3, FHX15, MGF4, MGF14 and MGF3 respectively. The first three devices are HEMTs and the last two are MESFETs.

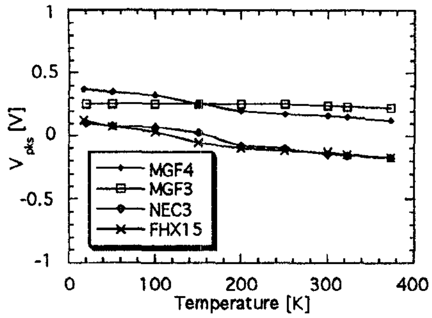

Fig. 4a. V_{pks} as function of temperature.

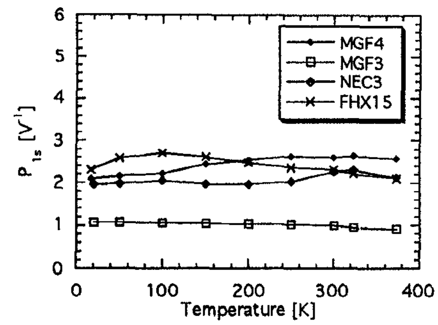

Fig. 7a . P_1 as function of temperature.

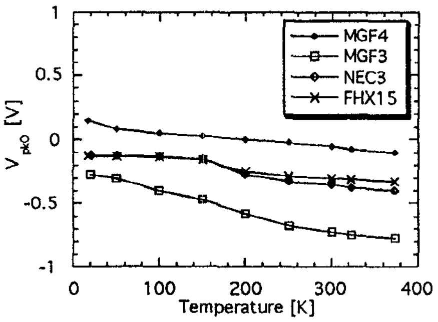

Fig. 4b. V_{pk0} as function of temperature.

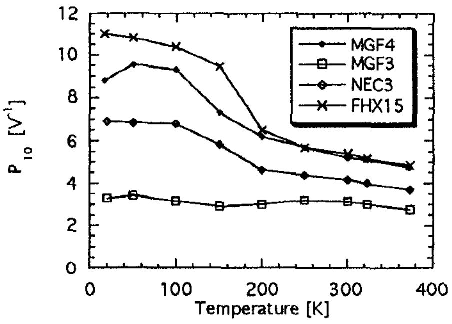

Fig. 7b. P_{10} as function of temperature.

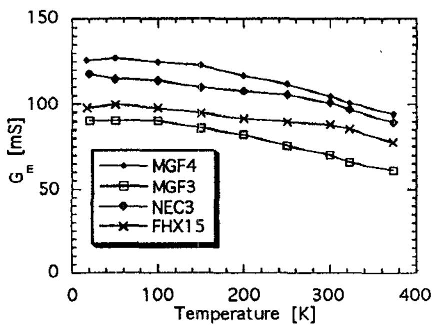

Fig. 5. The peak value of g_m as function of temperature.

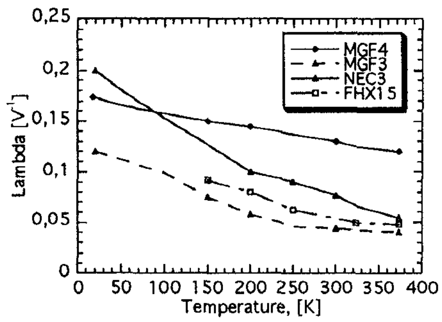

Fig. 8. l as function of temperature.

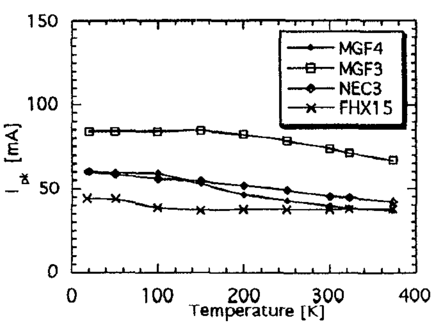

Fig. 6. I_{pk} as function of temperature.

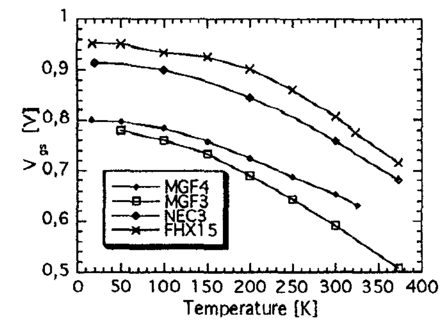

Fig. 9. V_{gs} as function of temperature, I_{gs}=0.5 mA.

The channel resistances r_{ch} and R_s are monotonically decreasing at low temperature, Fig. 10. The changes of the capacitances' C_{gs} and C_{gd} with the temperature are very small, approximately 20 % in the whole temperature interval 17K- 300K and these changes can be modelled quite accurately with linear functions.
Generally, in the temperature range 150-400K, the changes of the device parameters with temperature are usually smooth. These components variations with the temperature changes can be modelled with good accuracy using linear functions. Nearly all the measured devices have shown some unexpected behaviour in the temperature range 50-150K, e.g. collapse of the I-V characteristics, significant kink effects and strange shape of the transconductance curves. At lower temperatures (17-50K) the transistor characteristics are better, smoother and we have monitored much less unexpected effects. It appears that at the present stage it is difficult to make models that will describe the transistors in the entire temperature range 17-400K.
To obtain higher accuracy a quadratic term, A_2, can be added to the equation for the parameters variation with the temperature.

$$P(T) = P_0 + A_1 \Delta T + A_2 \Delta T^2 \qquad (9)$$

P(T) describe the temperature dependence of V_{pk0}, V_{pks}, I_{pk}, P_{1s}, P_{10}, l, V_{gs}, R_s, R_d, C_{gd}, C_{gs}. P_0 is the parameter value at room temperature, $\Delta T = T - T_0$, is temperature difference between ambient and room temperature. Linear temperature coefficients A_1 for the main parameters of the measured transistors are presented in Table 1. In fig. 11 we compare measured and simulated power spectrum [13] at 20K for MGF4317. MDS was used for the simulation and we believe that the correspondence is good.

Table 1. Linear coefficients for model parameters ($A_1 * 10^3$).

	I_{pks}	V_{pks}	V_{pk0}	P_{1s}	P_{10}	λ	α	R_s	C_{gs0}
MGF4317	-1.3	-2.7	-1.15	0.2	-1.6	-0.2	-1,01	1.3	0.7
MGF1303	-1.18	-0.6	-1.55	0.3	-0.67	-0.27	-0.1	0.7	
NEC3268	-1.23	-2.89	-2.06	0.7	-1.3	-0.36	-0.73	1.44	
FHX15	-0.46	-3.33	-1.45	-1.3	-1.75	-0.4	-0.2	1.08	

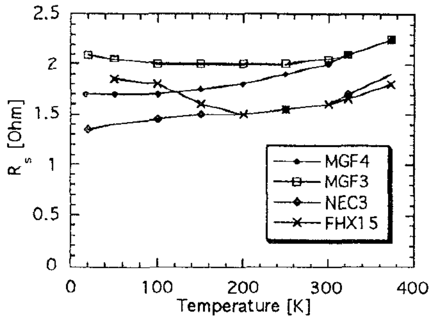

Fig. 10. R_s as function of temperature.

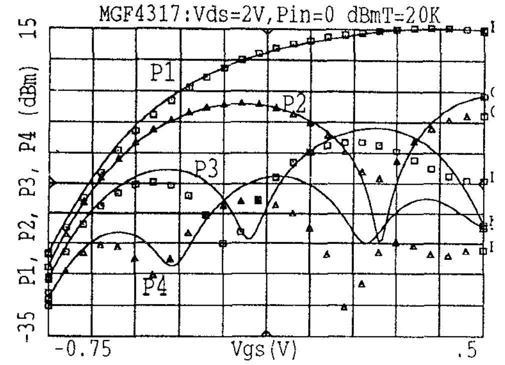

Fig. 11. Power spectrum as function of gate voltage for MGF4317.

CONCLUSIONS

Temperature and dispersion effects found in HEMTs and MESFETs have been investigated in the temperature range 17-400 K. The Chalmers nonlinear model was extended with the ability to model these effects.

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