TEMPERATURE-DEPENDENT MODELING OF HIGH POWER MESFET USING THERMAL FDTD METHOD

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ABSTRACT

— A temperature-dependent model of high power MESFET based on the small signal extraction methodology is presented. The temperature dependencies of the MESFET equivalent circuit elements derived from experimental results describing long-term thermal effects and short-term thermal effects have been modeled by means of FDTD method using chip dimensions. The verification of the proposed model shows an excellent agreement of the experimental results with the theoretical analysis.

I. INTRODUCTION

The amplifiers with GaAs MESFETs are essential devices in a broad spectrum of microwave systems applications including radiolocation, electronic warfare, satellite communications and telecommunications [1]. The high power GaAs MESFETs are currently the most common active devices used to design of microwave transmitters amplifiers. The typical military as well as some commercial applications require performance over a wide temperature range. For example, this temperature range is from -55^{o}C up to 125^{o}C. The temperature-dependent model of a high power MESFET is needed to predict the amplifier temperature behaviour during design. It allows to optimize the amplifier structure with respect to chosen parameters (output power, gain, etc.) and reduce the design and development costs of the circuits. The temperature-dependent models of GaAs MESFET are usually extracted from small output power transistors (P_{out}≤1W) and used to MMIC's design. The comparison of these models has been reported [2]. The common feature of these modeling procedures is the steady-state analysis. The self-heating effect appearing in a MESFET, very important for high power amplifiers, was taken into account in [3], but over a limited temperature range. The self-heating effect was described by means of drain current changes and modeled using the simple low-pass thermal circuit. The verification of the model was performed for small power FET and CW excitation.

In this paper, a complete temperature-dependent model for a high power GaAs MESFET is presented. The model includes the self-heating effect simulation and applies to switched DC – bias and RF pulse excitation. The temperature inside the transistor is calculated using transistor's chip dimensions. The two-dimensional finite difference method in time domain (FDTD) was applied for solution of heat conduction equation [4]. The proposed model allows to analyze and optimize a high power amplifier's structures taking temperature into consideration.

II. TRANSISTOR MODELING

A. Steady-State Model of High Power MESFET

The temperature-dependent model of high power A-class MESFET is extracted from S-parameters and DC characteristics at the ambient temperature. The high power MESFET model is shown in fig.1.

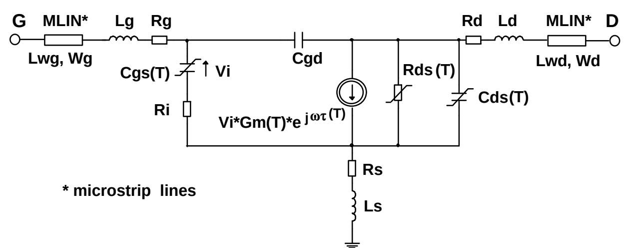

Fig.1. The temperature-dependent model of a high power GaAs MESFET

The temperature dependencies of equivalent circuit elements of MESFET were derived from many transistor [s]-matrixes measurements versus temperature. The most difficult problems in accurate measurements of the temperature dependence of S-parameters is due to the fact that $|S_{11}|$ is very close to unity and thus measurements of its value are very ill-conditioned. The problem was avoided by numerous measurements of many amplifiers over a wide temperature and frequency range. The measurement conditions were chosen to be such that $P_{out} << P_{DC}$ (the power of DC supply) and bias point was that suggested by manufacturer. These amplifiers with different GaAs MESFETs (for example: FLC053WG-$P_{1dB}=0.5W$, FLL171MK-$P_{1dB}=1.8W$, FLL351MK-$P_{1dB}=3.6W$(FUJITSU) and MITSUBISHI-MGF0907B-$P_{1dB}=10W$) were designed for maximum gain, output

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power level and for minimum AM-AM, AM-PM conversion. The transistors [S]-matrixes for each temperature were extracted from the amplifier measurements. The obtained results were used to work out the generalized temperature-dependent MESFET model. This approach is valid for the standard structure of MESFET. In order to extract MESFET model parameters for different output power level classical scaling process is used. We have introduced the following formulas for describing the temperature-dependent elements of MESFET model, shown in fig.1:

$$
\begin{aligned}
&C_{gs}(T_c,P_{1dB}) = C_{gs}(T_o)\left\{1+\left[-0.99+0.031\cdot \log(P_{1dB})\right]\cdot 10^{-3}\cdot (T_c-T_o)\right\}\\
&C_{ds}(T_c,P_{1dB}) = C_{ds}(T_o)\left[1+(-2.28-0.009\cdot P_{1dB})\cdot 10^{-3}\cdot (T_c-T_o)\right]\\
&G_m(T_c,P_{1dB}) = G_m(T_o)\left[1+(-2.29-0.03\cdot P_{1dB})\cdot 10^{-3}\cdot (T_c-T_o)\right] \qquad (1)\\
&R_{ds}(T_c,P_{1dB}) = R_{ds}(T_o)\left\{\begin{array}{l}1+\left[1.08-0.069\cdot \log(P_{1dB})\right]\cdot 10^{-3}\cdot (T_c-T_o)+\\ +(6.15+0.024\cdot P_{1dB})\cdot 10^{-6}\cdot (T_c-T_o)^2\end{array}\right\}\\
&t(T_c,P_{1dB}) = t(T_o)+\left\{\begin{array}{l}\left[-0.118+0.006\cdot \log(P_{1dB})\right]\cdot (T_c-T_o)+\\ +1.72\cdot 10^{-3}\cdot (T_c-T_o)^2+\\ +\left[2.2+0.112\cdot \log(P_{1dB})\right]\cdot 10^{-5}\cdot (T_c-T_o)^3\end{array}\right\}\cdot 10^{-12}
\end{aligned}
$$

where:

T_c - transistor case (metal) temperature

T_o - room temperature 25°C

P_{1dB} - output power at 1dB G.C.P.[W]

B. Transient Temperature Distribution

The model described previous point was derived for slow changes of temperature. The transistor case temperature does not change during short pulses, but the temperature inside the chip changes fast. The idea of the short pulses simulation consists in determining the transient temperature T_j in active area e.g. in channel area. The transistor parameters are calculated using this temperature T_j modified by the equation:

$$T_c = T_j - DT \qquad (2)$$

where:

T_c - the temperature of active area of transistor

DT - the difference between the transistor active area temperature and the case temperature for steady state

The DT can be calculated from catalogue data as:

$$DT = R_{thj\text{-}c} P_{DC} \qquad (3)$$

where:

$R_{thj\text{-}c}$ - thermal channel-to-case resistance

P_{DC} - DC power for nominal supply, RF-power off

This approach comes from the methodology of model extraction and permits to calculate the self-heating effect. The temperature of active area T_j is calculated taking into account the transistor chip structure. A typical chip of a power MESFET is presented in fig.2a [5]. It was assumed that, the temperature does not change along X-dimension. It means that the thermal analysis is made for the cross-section (fig.2b.) of the transistor's chip.

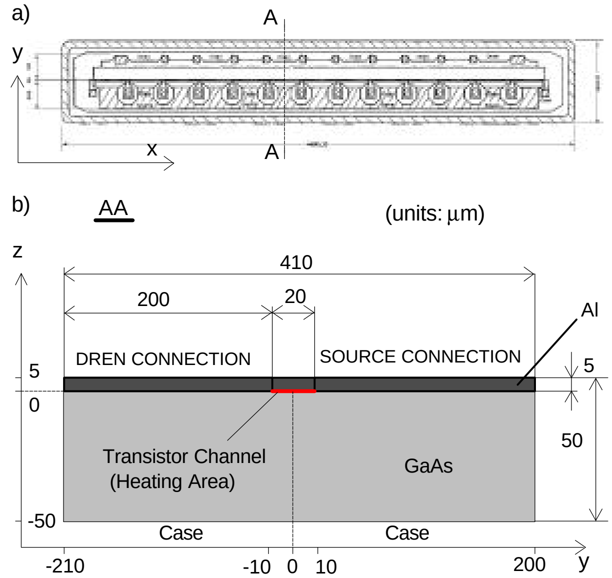

Fig.2. The chip of the typical MESFET, (a) top view, (b) cross-section.

The solution of the two-dimensional equation of heat conduction in this structure is needed for calculating the channel temperature T_j. In the case of homogeneous material the equation can be depicted as:

$$\frac{1}{a}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \qquad (4)$$

where:

$T=T(y,z,t)$ - temperature,

a - thermal diffusivity (0.44 cm^2/s for GaAs)

The analytical solution of the equation (4) is practically impossible for the MESFET structure. The only sensible way of this problem solution is a numerical method. The FDTD method [4] was applied. This method leads to substitution of derivatives in equation (4) by finite differences. It means discretization in space (fig.3) and in time.

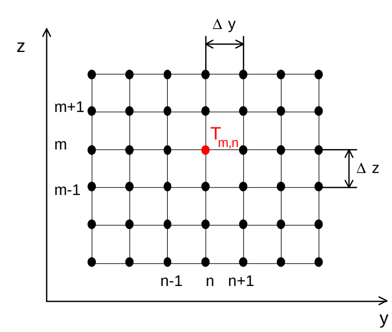

Fig.3. The Y-Z space discretization.

The temperature distribution across a chip for a next time step is calculated using current temperature distribution. The temperature at internal nodes $T_{m,n}$ of the structure shown in fig.3. is derived from the equation:

$$T_{m,n}^{p+1} = F_o \cdot \left(T_{m-1,n}^{p} + T_{m+1,n}^{p} + T_{m,n-1}^{p} + T_{m,n+1}^{p} \right) + \left(1 - 4 \cdot F_o\right) \cdot T_{m,n}^{p} \quad (5)$$

$$F_o = \frac{a \ D t}{(D \ y)^2} \quad (6)$$

where:

$T_{m,n}^{p+1}$ - the temperature in m,n node at p time moment

F_o - the Fourier factor

a - thermal diffusivity

Dt - time step

Dy - grid

$p+1$ - the next time moment

The equation (4) is derived from eq.(4) under assumption: $Dy=Dz$.

III. MODEL VERIFICATION

The proposed model of high power GaAs MESFET was experimentally verified. Transistor FLL120MK made by FUJITSU was chosen. The values of equivalent circuit of the transistor were extracted from S-parameters and DC characteristics at the ambient temperature $T_o=25^oC$ (catalogue). The values of the model elements are presented in fig.4. The L-band amplifier with FLL120MK transistor was designed for maximum output power [1]. The amplifier's output power at 1dB compression point is P_{1dB}³$10W$. The layout of the amplifier is presented on fig.5a. The characteristics of S_{11}, S_{21} and S_{22} versus temperature of the amplifier were measured using temperature chamber MK-53 (WTB-BINDER) and by means of network analyzer HP8720C. The comparison between measurements and simulations are shown in fig.5b.

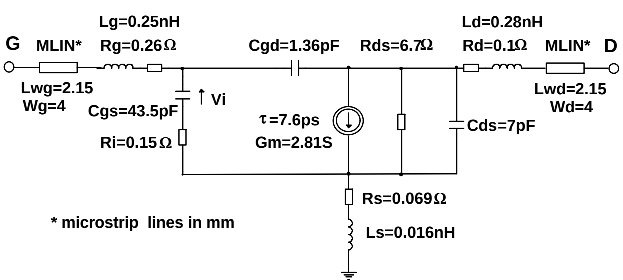

Fig.4. The model parameters at $T_o=25°C$, $U_{DS}=10V$, $I_D=2.2A$.

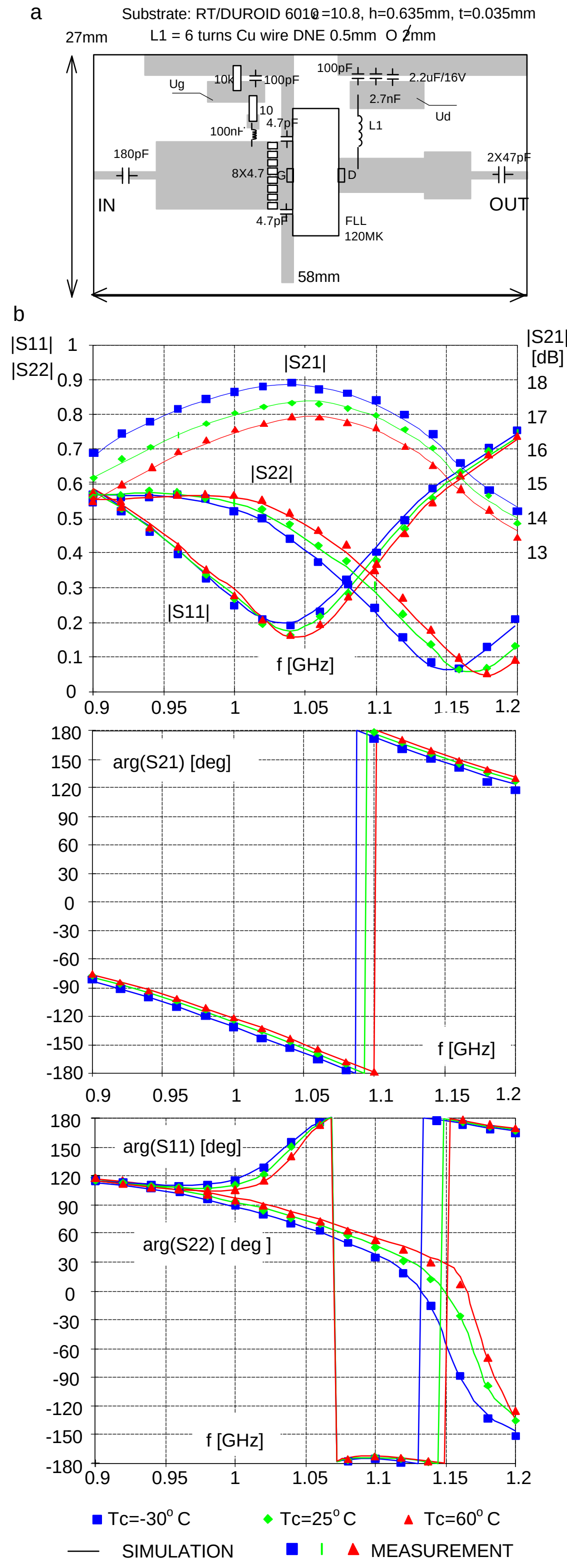

Fig.5. The layout of the high power amplifier with FLL120MK transistor (a). The measured and modeled S_{11}, S_{21}, S_{22} of power amplifier for the different case temperatures T_c (b).

The next measurements were performed for pulsed mode. The comparison of simulated and measured changes of arg(s_{21}) during RF pulse with high output power level $P_{out}=P_{1dB}=10W$ is presented in fig.6b. The test conditions are shown in fig.6a. The simulated temperature changes in active area of chip are shown in fig.6c. The simulated temperature distribution across the chip in different time moments is presented in fig.7.

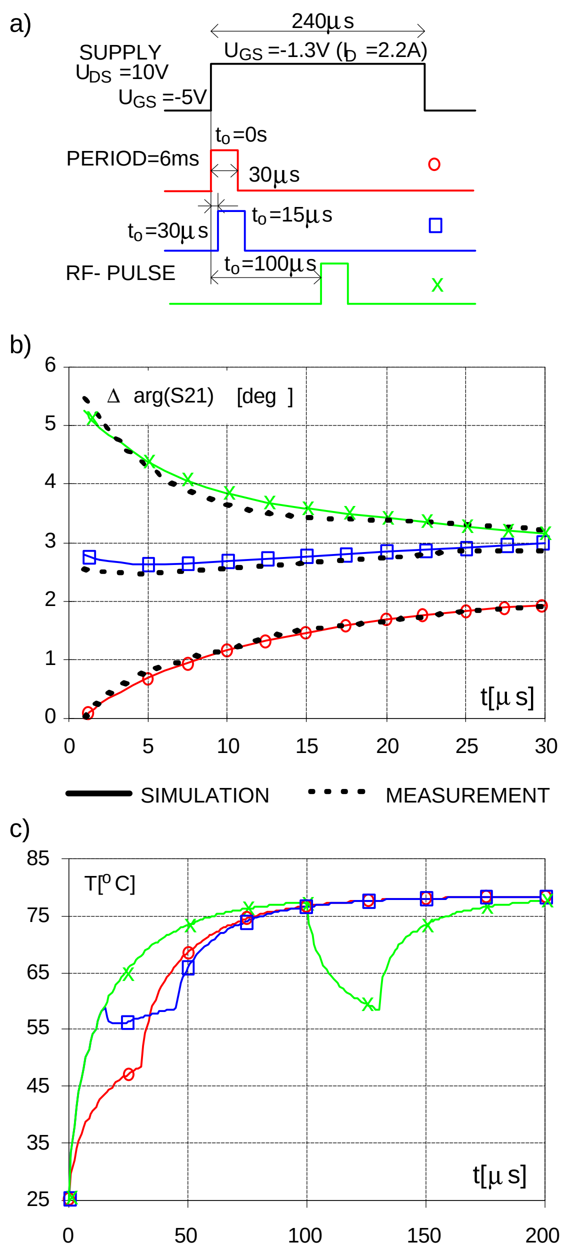

Fig.6. The comparison between simulations and measurements for $P_{out}=P_{1dB}=10W$. The test conditions (a), the measured and simulated *Darg(S_{21})* of amplifier during RF pulse (b), the simulated temperature changes of transistor active area (c).

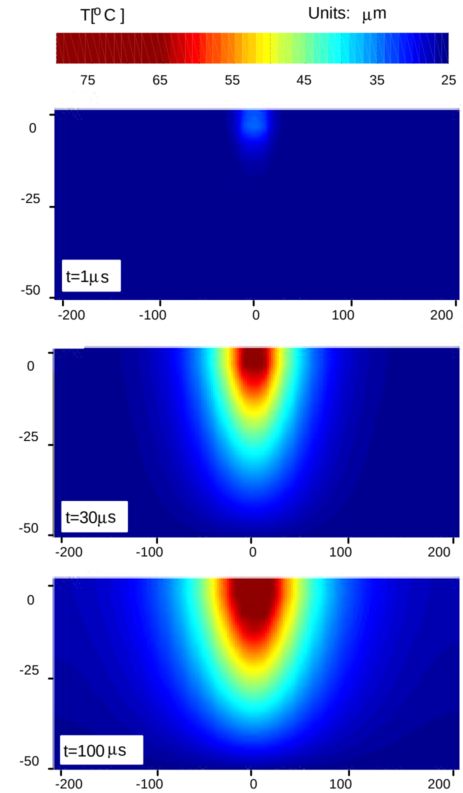

Fig.7. The simulated temperature distribution across the chip in different time moments (for test conditions $t_o=100ms$ - marked "x" in fig.6a).

IV. CONCLUSION

In this paper the temperature-dependent model for a high power GaAs MESFET was demonstrated. The obtained results show a good accuracy and usefulness of the proposed method for cw as well as pulsed conditions.

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