EMPIRICAL MODELING OF LOW-FREQUENCY DISPERSIVE EFFECTS DUE TO TRAPS AND THERMAL PHENOMENA IN III-V FETs*

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Abstract: *An empirical approach is proposed which accounts for low-frequency dispersive phenomena due to surface state densities, deep level traps and device heating, in the modeling of the drain current response of III-V FETs.*

The model, which is based on mild assumptions justified both by theoretical considerations and experimental results, has been applied to GaAs MESFETs of different manufacturers. Experimental and simulation results that confirm the validity of the model are provided in the paper.

INTRODUCTION

Deep level traps and surface state densities in III-V FETs, cause considerable deviations between "static" and "dynamic" (e.g., pulsed) measurements of the DC characteristics, or, if we think in terms of differential parameters, frequency dependent behavior of the trans-admittance and output impedance even at low frequencies (e.g., lower than 100KHz) [1..4].

Since microwave large-signal performance prediction involves accurate modeling of both DC and AC components of the drain current, efforts have been made to take into account low-frequency dispersion both in mathematical and equivalent circuit models [4..8]. In this context it must be emphasized that, when nonlinear operation is involved, simply substituting the static DC characteristics with the dynamic ones, necessarily leads to "local" models. The dynamic drain current deviations from static DC, in fact, are strongly dependent on the quiescent bias condition.

Another aspect that is worth considering is that the time constants associated with dynamic phenomena due to thermal effects, which become relevant in electron devices under large-signal operation, although somehow longer, are not always very different from those associated with traps or surface states (typically from fractions to hundreds of microseconds). Consequently, dispersion due to "traps" (with this term hereinafter we intend both surface states and deep level traps) cannot always be addressed separately from thermal phenomena due to power dissipation.

In the paper an empirical approach is described which takes into account both traps and thermal phenomena for the accurate modeling of deviations between static and dynamic (e.g., pulsed) drain characteristics in GaAs FETs. The experimental results provided in the paper are for GaAs MESFETs, but the same approach should be valid for other III-V electron devices (e.g., HEMTs).

THE MODELING APPROACH

As far as steady-state microwave circuit simulation is concerned (i.e., circuit analysis based on Harmonic-Balance techniques), the lowest RF spectral component of interest is usually well above the upper cut-off frequencies (from tens to hundreds of KHz) associated to low-frequency dispersive phenomena. Under such conditions, any possible set of state variables $\underline{x}$ (e.g., equivalent surface potentials, trap level filling, etc...) used to describe the "slow" dynamic phenomena associated with the traps is practically coincident with its DC value $\underline{X_0}$, that is $\underline{x(t)} \simeq \underline{X_0}$. The same consideration is obviously valid for the internal temperature $\theta(t) \simeq \theta_0$, that in the context of circuit-analysis-oriented modeling is assumed to be uniform along the channel. Thus, at frequencies above the cut-off of dispersive phenomena but low enough to neglect microwave reactive effects due to junction charge-storage or transit times,

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the drain current of a III-V FET can be expressed in the form:

$$i_D(t) = \Phi\left[v_G(t), v_D(t), \underline{X_0}, \theta_0\right] \quad (1)$$

where Φ is a purely algebraic nonlinear function and v_G, v_D (in the following, lower-case letters will denote time-dependent quantities) are the gate and drain voltages.

Description (1) is obviously too general to be practically useful: some simplifying hypothesis must be necessarily introduced to obtain a model easy to identify and suitable for the computer-aided analysis and design of integrated circuits.

The empirical model is based on the main assumption, which has been partially justified also by experimental and simulation results, that the vector $\underline{X_0}$ of the DC components of the state variables associated to the traps is dependent only on the mean values V_{G0}, V_{D0} of the external voltages $v_G(t)$, $v_D(t)$. This implies that $\underline{X_0}$ is not significantly affected by the amplitude and "shape" of the alternate components $v_G(t) - V_{G0}$ and $v_D(t) - V_{D0}$; in other words it is assumed that the nonlinear effects possibly related to traps, are not so strong to involve relevant AC to DC conversion in the relation between $v_G(t)$, $v_D(t)$ and $\underline{x}(t) \simeq \underline{X_0}$. Such an assumption can be also intuitively justified by observing that the regions of the device where traps are located (i.e., gate-source and gate-drain surface regions, channel-substrate interface) are not directly responsible for important nonlinear effects. Moreover, large-signal equivalent circuits or numerical physics-based models proposed by many authors, directly or indirectly lead to analogous conclusions.

On the bases of the above considerations, description (1) can be approximated by:

$$i_D = \mathcal{F}[v_G, v_D, V_{G0}, V_{D0}, \theta_0] \quad (2)$$

which points out how, in the presence of low-frequency dispersive phenomena, the drain current is a function not only of the instantaneous gate and drain voltages $v_G(t)$ and $v_D(t)$, but also of their mean values V_{G0}, V_{D0} and the mean value θ_0 of the internal temperature.

Practical considerations suggesting that the dynamic phenomena due to traps and device heating, although by no means negligible, are usually not so strong to involve highly nonlinear effects[1], also suggest that, as a first level of approximation, eqn. (2) could be linearized with respect to V_{G0}, V_{D0} and θ_0 in the neighborhood of suitably chosen *"nominal"* operating conditions V_{G0}^*, V_{D0}^* and θ_0^*. This can be also justified by considering that many microwave circuits operate with practically constant values, or with limited variations, of the DC bias voltages on active devices.

Linearization of (2), leads, after simple algebraic manipulations, to the simplified expression:

$$i_D = F_{DC}^*[v_G, v_D] + \quad (3)$$

$$f_\theta[v_G, v_D][R_\theta(P_0 - P_0^*) + \theta_C - \theta_C^*] \; +$$

$$+ f_G[v_G, v_D](v_G - V_{G0}) + f_D[v_G, v_D](v_D - V_{D0})$$

where $f_G = -\left.\frac{\partial \mathcal{F}}{\partial V_{G0}}\right|_*$, $f_D = -\left.\frac{\partial \mathcal{F}}{\partial V_{D0}}\right|_*$, $f_\theta = \left.\frac{\partial \mathcal{F}}{\partial \theta_0}\right|_*$, $F_{DC}^* = \mathcal{F}|_* + f_G(V_{G0}^* - v_G) + f_D(V_{D0}^* - v_D)$. The dependence of the internal temperature on the dissipated power has been expressed in (3) through an approximated model of the type $\theta_0 - \theta_C = \psi(P_0)$ and we have introduced the thermal resistance $R_\theta = \partial\psi/\partial P_0|_*$.

In (3), f_G and f_D are suitable functions which account for drain current deviations, due to trapping phenomena, from the static DC behavior; the function f_θ, instead, accounts for deviations due to device heating/cooling (caused by power dissipation and/or by changes in the case temperature θ_C) with respect to an "ideal" equi-thermal DC characteristic F_{DC}^*. The latter could be, for instance, the "ideal " DC characteristic obtained by conventional physics-based numerical device simulations where temperature variations deriving from power dissipation are neglected.

The experimental characterization of model (3) can be carried out on the bases of DC static and dynamic measurements. In particular, if the device thermal resistance R_θ is known, the four functions F_{DC}^*, f_θ, f_G and f_D can be identified by a model *fitting* procedure based on a suitably large number (the minimum required is 4) of static and dynamic (e.g., pulsed) measurements. More precisely, for each value of $v_G(t)$ and $v_D(t)$, a least square algorithm can be adopted to solve a linear system of equations, of the type (3), for the unknown terms F_{DC}^*, f_θ, f_G and f_D (the known terms being the static and pulsed measurements of i_D). In our experience, we have found that if the quiescent bias conditions for the pulsed measurements are chosen according to a suitable criterion [9], a minimum number of four sets of pulsed

[1]The most important nonlinear phenomena in a field-effect electron device mainly derive from direct modulation of the channel conductance due to $v_G(t)$ and $v_D(t)$.

measurements is sufficient to consistently identify the terms F_{DC}^{*}, f_θ, f_G and f_D.

The above procedure, where static and pulsed measurements are performed only at a single case temperature (for instance the ambient temperature), can be adopted also when the thermal resistance is unknown if we are not interested in predicting drain current deviations due to changes of the case temperature. In such conditions, the model (3) is obviously valid at the chosen case temperature $\theta_C = \theta_C^*$ and (3) can be simplified by introducing the function $f_p[v_G, v_D] = f_\theta[v_G, v_D]R_\theta$, which accounts only for drain current deviations caused by device heating/cooling due to power dissipation; f_p can be identified according to the same above-described procedure.

The availability of static and pulsed measurements at different case temperatures enables the different causes of internal temperature variations (i.e., device heating/cooling due to power dissipation from one side and to changes in the case temperature on the other one) to be exploited for thermal resistance "extraction" [9]. In particular, the same model *fitting* procedure described above can be adopted on the bases of static and pulsed measurements at different temperatures to consistently "extract" also the unknown parameter R_θ. Under such conditions, all of the terms required in (3) to predict deviations of the drain current due to traps, power dissipation and/or changes of the case temperature can be identified by using the same measurement equipment.

Once the functions F_{DC}^{*}, f_θ, f_G and f_D have been identified, their value can be stored into look-up tables and used, in conjunction with (3) (and suitable interpolation techniques) to predict the drain current behavior in the low-frequency range above thermal and trapping cut-off.

When microwave circuit simulation is concerned, obviously the dispersive model proposed must be embedded in an RF model. This can be accomplished quite easily [8,9], both for mathematical [6,7] and equivalent circuit models.

EXPERIMENTAL RESULTS

The experimental validation of the proposed model has been carried out on the basis of a large number of static and dynamic (e.g., pulsed) measurements of the drain current performed on GaAs MESFETs of different manufacturers.

The model functions F_{DC}^{*}, f_θ, f_G and f_D, have been identified on the bases of a minimum set of pulsed measurements (corresponding to four different quiescent bias conditions). In the case of the CFX32 device, also the thermal resistance R_θ has been "extracted" from measurements at different temperatures; the value obtained ($58^oC/W$) is in good agreement with the value provided by the manufacturer ($60^oC/W$).

As an example some comparison between measurements and results **predicted** by the model, for different GaAs MESFETs, are shown in Figs.1..12. It must be emphasized that the set of measurements provided in these figures were carried out for temperatures and quiescent bias conditions different from those used for model identification. This validates the model capability of **predicting** the dependence of the dynamic drain characteristics on bias conditions, temperature and dissipated power.

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Fig.1..12: "Static" and "dynamic" (e.g., pulsed) DC drain current. Comparison between experimental results (•) and model prediction (—) for GaAs MESFETs of different manufacturers.