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Modelling of low-frequency dispersive effects in GaAs and InP HEMTs

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Abstract A previously proposed approach for modelling the dispersive effects in III-V FET devices is applied to InP and GaAs HEMTs in order to verify its validity also for heterostructure-based devices and to confirm its technology independence. Both surface states, bulk traps and thermal dispersive phenomena are simultaneously taken into account to allow for a better prediction of the deviations between dynamic (e.g., pulsed) and static drain current characteristics.

Introduction

Accurate nonlinear modelling of III-V FETs for microwave circuit design should also account for low-frequency dispersive phenomena of the electrical characteristics due to deep level traps and surface state densities. These phenomena cause considerable, bias-dependent deviations between "static" and "dynamic" (e.g., pulsed) measurements of the DC characteristics, or, in terms of differential parameters, frequency dependent behavior of the trans-admittance and output impedance even at low frequencies (e.g., lower than 100KHz).

It is worth noting that the time constants associated with dynamic phenomena due to thermal effects (which become relevant in an electron device when large-signal operation is concerned) although somewhat longer, are not very different from those associated with traps or surface states (both range 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.

Since microwave large-signal performance prediction involves accurate modelling of both DC and AC components of the drain current, efforts have been made to take into account low-frequency dispersion in nonlinear models for microwave circuit analysis and design [1..5]. In particular, technology-independent models are very appealing as new electron devices based on advanced technologies and materials (e.g., InP) become rapidly available.

In this paper a modelling approach (which takes into account both traps and thermal phenomena) previously applied to GaAs MESFETs [4] is adopted for the accurate modelling of deviations between the static and dynamic drain current[1] in GaAs and InP HEMTs. The main goal is to validate the technology independence of the proposed approach.

Model Description

The modelling approach adopted [4] is mainly oriented to steady-state microwave circuit simulation (i.e., circuit analysis based on Harmonic-Balance techniques). For microwave circuits, the smallest frequency of interest, apart from DC, is at least several MHz, i.e., well above the upper cut-off frequencies associated with low-frequency dispersive phenomena. Under such conditions any chosen set of state variables $\underline{x}$ (e.g., equivalent surface potentials, trap level filling, etc...) which describe the "slow" dynamic phenomena associated with the traps, is practically coincident with the DC value $\underline{X_0}$, i.e., $\underline{x}(t) \simeq \underline{X_0}$.

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[1] The model for the drain current can be easily embedded in an RF model for microwave circuit analysis.

The technology independent model is based on the main assumption, which has been justified also by experimental and simulation results [4,6], that the vector $\underline{X_0}$ of the DC components of the state variables associated with the traps depends 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.

As far as heating effects are concerned, a linear[2] thermal model has been adopted to describe the dependence of the intrinsic device temperature θ (which, in this context, is assumed to be uniform) on the power dissipated in the device.

On the basis of the above assumptions, the drain current i_D, at frequencies above the cut-off of thermal and trapping phenomena but low enough for microwave reactive effects to be negligible, can be expressed in the following form:

$$i_D(t) = \mathcal{F}[v_G(t), v_D(t), V_{G0}, V_{D0}, P_0] \qquad (1)$$

where P_0 is the average dissipated power.

A linearisation of (1) with respect to V_{G0}, V_{D0} and P_0 in the neighbourhood of *"nominal"* operating conditions V^*_{G0}, V^*_{D0} and P^*_0 can be performed to obtain an approximated but easily identifiable expression. This is justified by observing that dynamic phenomena due to traps and device heating, although by no means negligible, are usually not so strong to involve highly nonlinear effects. Moreover, especially when mild nonlinearities in the microwave circuit are involved, the bias point is often subjected only to limited variations around the nominal condition.

The linearized approximated form of (1), after simple algebraic manipulations, can be written as:

$$i_D\{v_G, v_D\} = \widehat{F}_{DC}\{v_G, v_D\} + f_G\{v_G, v_D\}(v_G - V_{G0}) + f_D\{v_G, v_D\}(v_D - V_{D0}) + f_P\{v_G, v_D\}(P_0 - P^*_0) \qquad (2)$$

In the above equation, f_G and f_D are functions which account for drain current deviations, due to trapping phenomena, from the static DC behavior; the function f_P, instead, accounts for deviations due to device heating with respect to an "ideal" isothermal DC characteristic $\widehat{F}_{DC}$. The latter could be, for instance, the "ideal" DC characteristic obtained by a conventional physics-based numerical device simulation where temperature variations produced by power dissipation are neglected.

When microwave circuit simulation is concerned, obviously the dispersive model (2) must be embedded in an RF model. This can be accomplished quite easily both for mathematical and equivalent circuit models [4].

Model Identification

The identification of the model described in the previous section requires the evaluation of the four functions $\widehat{F}_{DC}$, f_G, f_D, f_P on a suitable grid of voltages v_G, v_D. In fact, once these functions are known, their values can be stored in lookup tables and used in conjunction with equation (2) and suitable interpolation techniques to predict the drain current behavior in the low-frequency region above thermal and trapping cut-off.

A possible identification procedure is based on the knowledge of a suitably large number of pulsed measurements performed for different quiescent bias conditions V_{G0}, V_{D0} (a DC set may also be included). In particular, for each value of $v_G(t)$ and $v_D(t)$ a least-squares algorithm can be adopted to solve (for the unknown terms F^*_{DC}, f_P, f_G and f_D) a linear system of equations composed of different

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[2] Actually, heat conduction is affected by nonlinear phenomena; however, as the experimental results have confirmed, the linear approximation is still acceptable when the basic aim is the macroscopic modelling of the effects of low-frequency dispersion above cut-off.

instances of (2), each obtained for an i_D term measured by pulsing from a different quiescent condition V_{G0}, V_{D0}. Although a large number of pulsed measurements allows for a more robust identification of the model, a minimum set of pulsed measurements has been proved in many cases to provide sufficiently good results. For MESFET devices, for example, four pulsed drain measurement sets plus the DC set have been successfully employed, as can be seen in [4] and in Fig.1. Although it is not strictly necessary to include the static measurements in the model identification procedure (since four dynamic measurements are sufficient to identify the four functions F^*_{DC}, f_P, f_G and f_D), a slightly better accuracy in the modelling of the DC characteristics has been obtained with their inclusion. As far as the criterion for the choice of the minimum set of pulsed measurements is concerned, the best results have been obtained considering values of V_{G0}, V_{D0} which correspond to sensibly different operating regions of the device with respect to traps and thermal phenomena (e.g., pinch-off and wide open channel bias conditions with both low and high values of V_{D0}).

Experimental Results

The basic assumptions which lead to model (2) are substantially technology-independent and preliminary results, which confirm this interesting aspect of the modelling approach have been presented in [4]. Here more results are given for on-wafer measured GaAs and InP heterostructure HEMTs and a MESFET device.

In Figs.1..2 a comparison between measured and predicted dynamic drain characteristic versus V_{DS} is shown for a 300 μm GEC-Marconi GaAs-MESFET device (L=0.5 μm) and an IMEC δ-doped $Al_{0.25}Ga_{0.75}As/In_{0.2}Ga_{0.8}As/GaAs$ 100 μm pseudomorphic HEMT (L=0.25 μm). In Figs.3..6 drain current measurements and predictions of the model versus V_{GS} are compared for the same GaAs HEMT and an IMEC δ-doped $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/InP$ 100 μm HEMT (L=0.3 μm).

It must be emphasized that the results provided in these figures are obtained under quiescent conditions **different from those used for model identification** in order to validate the "actual" predictive capabilities of the model. Despite the moderate dispersion of dynamic characteristics[3] (especially for InP devices), the model is capable of accurately predicting their dependence on quiescent bias conditions and dissipated power.

The experimental results demonstrate that this modelling approach is really technology-independent, as it can be successfully adopted for a variety of III-V FETs.

References

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[3] The moderate dispersion of dynamic characteristics could be a macroscopic proof of the good quality of the device technology from the point of view of traps and surface states.

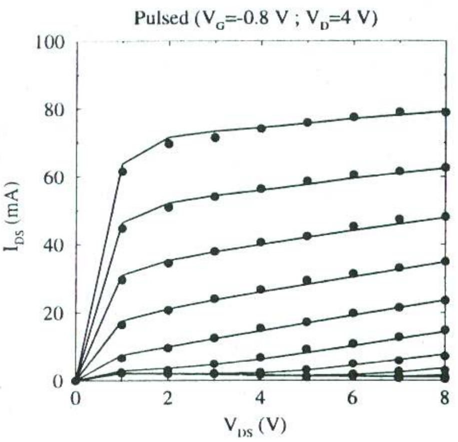

Fig.1: Measured and predicted dynamic drain current characteristics for a 4x75 μm GEC GaAs MESFET (L=0.5 μm).

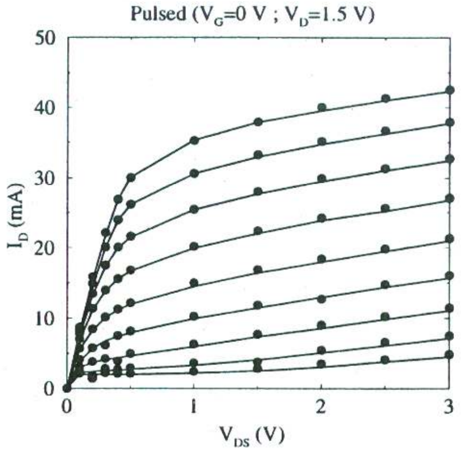

Fig.2: Measured and predicted dynamic drain current characteristics for an IMEC δ-doped $Al_{0.25}Ga_{0.75}As/In_{0.2}Ga_{0.8}As/GaAs$ pseudomorphic HEMT (L=0.25μm, W=100 μm).

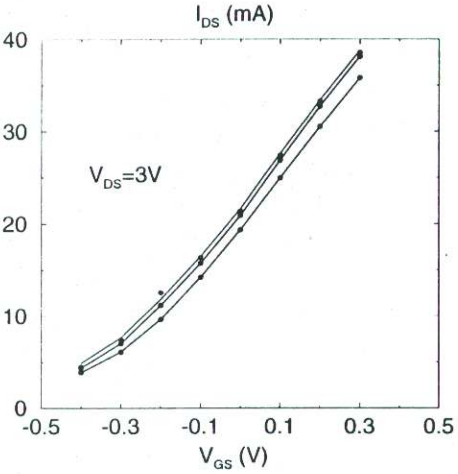

Fig.3: Measured and predicted dynamic drain current characteristics for different quiescent bias conditions of the same device of Fig.2.

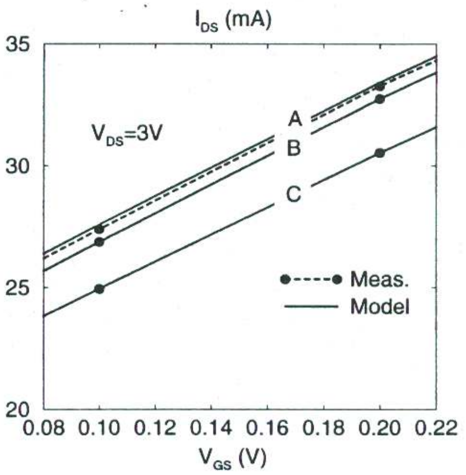

Fig.4: Enlarged view of Fig.3. The quiescent bias conditions are: **A**: $V_{GS0} = +0.3$, $V_{DS0} = 1.5$; **B**: $V_{GS0} = +0.3$, $V_{DS0} = 0$; **C**: $V_{GS0} = -0.3$, $V_{DS0} = 0$.

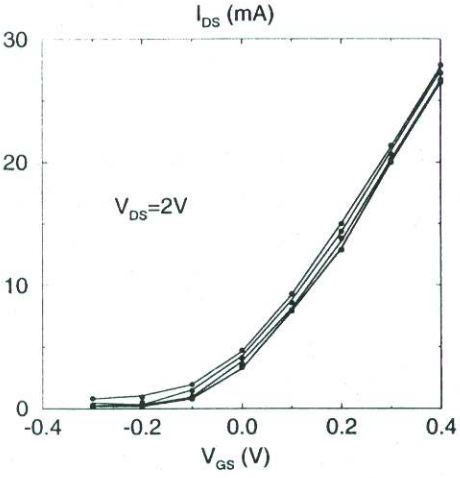

Fig.5: Measured and predicted dynamic drain current characteristics for different quiescent bias conditions for an IMEC δ-doped $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/InP$ HEMT (L=0.3 μm, W=100 μm).

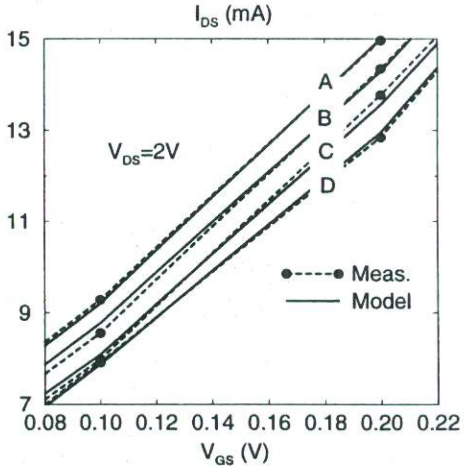

Fig.6: Enlarged view of Fig.5. The quiescent bias conditions are: **A**: $V_{GS0} = +0.3$, $V_{DS0} = 2$; **B**: $V_{GS0} = +0.3$, $V_{DS0} = 1$; **C**: $V_{GS0} = -0.2$, $V_{DS0} = 1$; **D**: $V_{GS0} = -0.2$, $V_{DS0} = 0$.