GAAS® 97 • 5th European Gallium Arsenide and related III-V compounds Applications Symposium
Bologna, Italy - September 3rd-5th, 1997

A novel approach to yield estimate and IMP performance optimization of microwave devices

S. Donati Guerrieri, F. Bonani, M. Pirola, G. Ghione and F. Filicori[†]

Dipartimento di Elettronica, Politecnico di Torino,
Corso Duca degli Abruzzi 24, Torino, Italy
[†]*Dipartimento di Elettronica, Informatica e Sistemistica, Università di Bologna,*
Viale Risorgimento 2, Bologna, Italy

Abstract

This paper presents an efficient, physics-based approach to evaluate the large-signal (LS) parametric sensitivity of microwave devices operated in (quasi) periodic conditions. The approach is based on the combined use of a two-dimensional drift-diffusion physical model and of an intermediate circuit-oriented large-signal model. The LS parametric sensitivity is then exploited to optimize the doping profile of a GaAs MESFET so as to minimize the third-order intermodulation products (IMP) in a simple large-signal amplifier. An example of yield-oriented statistical analysis of device performances with respect to random variations of technological parameters is also presented.

1 Introduction

As a matter of principle, the superiority of the physics-based approach in the performance and yield optimization of (Monolithic) Microwave Integrated Circuits, (M)MICs is well established [1]. Nevertheless, from a practical standpoint the approach has not yet become widespread enough in foundry-level circuit and device design, despite the success achieved in several case studies. Among the difficulties physics-based approaches are fraught with we can quote, first, accuracy and consistency problems related to both the models and the input parameters; second, the unavailability of efficient CAD techniques for parametric optimization and yield analysis in the field of accurate physics-based models.

Concerning the first point, the viability of physics-based models as practical design tools in production-oriented environments has been often advocated and demonstrated; however, it is often felt that the computational cost of such models is too high when compared to the benefits (M)MIC production can achieve from their use. In fact, physics-based models can be effectively exploited as accurate predictive tools (and not only to explore trends and investigate new solutions) only in the presence of a sound tuning of some critical physical parameters on measured data. Unless this technology-dependent process is carried out, also complex, multidimensional models based on the solution of transport equations can fall short of the expectations [2].

Concerning the second point, accurate (and therefore complex) physics-based models have been till now analysis rather than design tools. Optimization through repeated analyses can be extremely time-consuming; moreover, this process becomes useless unless a proper optimization goal has been established. In particular, the development of some circuits requires the device to be optimized with respect to a very specific, often large-signal circuit (not only device) performance. In such conditions, simplified strategies based on the maximization of simple parameters (like the DC transconductance or the DC transfer curve linearity) may be insufficient.

In this paper, we present a novel development in the field of physics-based CAD techniques, *i.e.* an efficient method to evaluate the effect of small variations of input technological and physical parameters σ of the microwave LS electrical device performances γ, *i.e.* the device *small-change LS parametric sensitivity* S_σ^γ. The evaluation of device sensitivity enables to apply efficient, gradient-based techniques to the LS device optimization, but also to carry out a statistical device analysis with respect to random variations of physical or technological input parameters [3]. For the first time (as far as our knowledge goes) a full technological optimization case study of a microwave FET is presented, having as the design goal a LS performance (the minimization of IMP). An extended version of the present work has already been published in [4].

2 The approach

Small-change parametric sensitivity evaluation can be generally performed by means of a first-order perturbation approach, whereby the model is analyzed in nominal conditions, and the effect of a small-amplitude variation of technological parameters is estimated from the solution of a linearized model. A direct application to physics-based device models has been proposed in [5]. A more efficient method, derived from the sensitivity evaluation of electrical networks [6], has been applied by some of the present authors to the DC sensitivity analysis of microwave FETs in [7] by means of a drift-diffusion two-carrier 2D model. Extension to the AC small-signal (SS) and large-signal cases is less straightforward. Examples of AC LS sensitivities are, for instance, the sensitivity of the output harmonics of a power amplifier driven into saturation by a frequency-dependent input signal with respect to the doping of the active region, or the sensitivity of the IMPs from a low-power amplifier with respect to the channel implant energy. Under general, quasi-periodic, multi-tone excitation LS sensitivies depend on the amplitude and frequency of the input tones.

While the evaluation of AC SS sensitivities requires, as discussed in detail in [4], a second-order model (mixed) differentiation, which is both cumbersome and possibly affected by numerical problems, the LS case is, at first sight, even more difficult. In fact, in the LS nominal operating conditions the device is embedded in a network and generally driven by a multi-tone LS excitation. Since the physics-based LS analysis is already a formidable problem, sparsely addressed in the literature [8, 9, 10] only for the strictly periodic case, direct linearization around the instantaneous working point according to the so-called small-signal large-signal approach looks thoroughly unpractical.

Following the strategy outlined in [2], we propose an alternative, more efficient approach to physics-based LS sensitivity evaluation. The method is described in more detail in [4]; here, only a short summary will be provided. The basic idea is to carry out the LS nominal and sensitivity analyses at a circuit level, making use of an accurate LS model derived from DC and SS physics-based simulations of the (almost) intrinsic device. An excellent, device-independent candidate as an intermediate circuit-oriented model is the so-called Nonlinear Integral Model (NIM) proposed by Filicori, Vannini and Monaco [11]; as shown in [11] the model accuracy in reproducing the result from multidimensional simulations is excellent. Moreover, a quasi-static version of the NIM equivalent to more convential LS equivalent circuit models [12] can be exploited to further simplify the problem. In fact, in this case the model can be identified on the basis of DC current and charge simulations and their sensitivities, thereby avoiding the use of AC SS sensitivities [4].

We applied the previously outlined method to the 2D two-carrier device simulator BOSS, developed during the last few years at Politecnico di Torino. By repeated DC simulations over a range of bias voltages we derived the bias-dependent drain current and gate stored charge, $I_D(V_{GS}, V_{DS})$ and $Q_G(V_{GS}, V_{DS})$, respectively, and their sensitivity with respect to some technological parameter. This was chosen to be the doping profile, described either as a set of samples, or through a multiple-implant set of Gaussian profiles. In the latter case, which was then exploited for device optimization, technological parameters are the implant projected range and straggle. On the basis of the current and charge data, a simple LS intrinsic model was identified, completed with suitable parasitics, and inserted in a LS network to be analyzed at a circuit level by means of a multi-tone harmonic-balance (HB) technique exploiting the so-called random sampling approach. Standard conversion matrix techniques were then applied to evaluate the perturbation network and therefore the sensitivity of the circuit solution (e.g. the load harmonics) with respect to the technological parameters. Finally, the whole model was embedded into a gradient-based simulation loop devised to optimize the device with respect to technological parameters (in this case, those controlling the doping profile).

3 Examples

We now present some examples concerning the sensitivity analysis, statistical analysis and optimization of a 0.5 μm GaAs MESFET performed with respect to the doping profile. Fig.1 and Fig.2 show the *distributed sensitivity* $s^{\gamma}_{\sigma}(\underline{r})$, with respect to doping variations, of the drain current and gate charge on the device cross section for the DC bias point $V_{DS} = 3$ V, $V_{GS} = -0.4$ V, wherein $s^{\gamma}_{\sigma}(\underline{r})$ is that function whose spatial integral over the device domain yields S^{γ}_{σ} (see [7] for details). Typical computation times for a 1500 node simulation on a HP 735/125 workstation are 30 s for the DC solution and about 5 s for the DC sensitivity. As can be seen, in both cases the device region mainly contributing to the electrical performance variation is that under the gate.

An example of statistical analysis performed through the sensitivity approach is shown in Fig.3, wherein the linear approximation stochastic spreading (continuous line) in the saturation drain current due to a gaussian distribution in the implant energy for a one-implant device is compared to the histogram resulting from a direct, Monte Carlo-based evaluation performed through the 2D physical model. The standard deviation corresponding to a 10 keV spreading in the implant energy is 1.19 mA for the Monte Carlo approach and 1.15 mA for the sensitivity model.

The sensitivity analysis can also be applied to the gradient-based optimization of the device doping profile to achieve a proper goal: DC sensitivity has been used to obtain maximum linearity in the transcharacteristics (constant g_m *vs.* V_{GS}), and a quasi-static approach has been applied to minimize the intermodulation products due to a LS, two-tone, quasi periodic excitation. Fig.4 shows the doping profiles for an epitaxial 0.5 μm MESFET, a two-implant device used as the initial condition for the g_m optimization and the results obtained for the two optimization tasks previously described. The maximum linearity device (see Fig.5 for a comparison of the initial, optimized and objective transcharacteristics) has the doping profile shown in Fig.4 with the continuous curve. The device optimized for the intermodulation products, instead, is characterized by the dash-dotted doping profile (Fig.4). In Fig.6 the $P_{\text{in}} - P_{\text{out}}$ curves at the fundamental frequencies (10 GHz and 10.1 Ghz), the 20 GHz second harmonic and the third-order intermodulation product (9.9 GHz) are shown for the epitaxial device, the device optimized for the DC maximum linearity and the LS optimized device. A significant advantage (about 20 dBm) is obtained on the whole P_{in} domain.

4 Conclusions

An efficient technique for the physics-based sensitivity analysis of microwave devices and circuits under LS (quasi) periodic excitation has been presented. Examples of statistical analysis and parametric optimization of a MESFET under LS operation have been presented, thus demonstrating the feasibility of the approach.

Acknowledgements

The research was partially supported by the Italian Ministry of Research through the MIA (*Materiali Innovativi Avanzati*) project, and by the National Council of Research (CNR) through the project SAI (*Sistemi autronici a iperfrequenze*).

References

[1] *IEEE Trans. on Microwave Theory & Techniques*, Special Issue on "Process-oriented microwave CAD modeling", Vol.40, N.7, July 1992.

[2] F. Filicori, G. Ghione and C. Naldi, "Physics-based electron device modelling and computer-aided MMIC design", *IEEE Trans. on Microwave Theory & Techniques*, Special Issue on "Process-oriented microwave CAD modeling", Vol.40, N.7, pp.1333-1352, July 1992.

[3] J. W. Bandler, R. M. Biernacki, Q. Cai, S. H. Chen, S. Ye and Q.-J. Zhang, "Integrated physics-oriented statistical modeling, simulation and optimization", *IEEE Trans. on Microwave Theory & Techniques*, Special Issue on "Process-oriented microwave CAD modeling", Vol.40, N.7, July 1992, pp.1374-1400.

[4] F. Bonani, S. Donati, F. Filicori, G. Ghione, M. Pirola, "Physics-based large-signal sensitivity analysis of microwave circuits using technological parametric sensitivity from multidimensional semiconductor device models", *IEEE Trans. Microwave Theory Techn.*, Vol. MTT-45, No. 5, pp. 846–855, May 1997.

[5] A. Gnudi, P. Ciampolini, R. Guerrieri, M. Rudan and G. Baccarani, "Sensitivity analysis for device design", *Proc. of ESSDERC 87*, pp. 551–554, Bologna, Sept. 1987, and *IEEE Trans. on CAD*, Vol.CAD-6, No. 5, Sept. 1987, pp. 879–885.

[6] F. H. Branin, "Network sensitivity and noise analysis simplified", *IEEE Trans. on Circuit Theory*, Vol. CT-20, No.3, pp.285-288, May 1973.

[7] S. Donati, F. Bonani, M. Pirola, G. Ghione, "Sensitivity-based optimization and statistical analysis of microwave semiconductor devices through multidimensional physical simulation", Invited Paper in *Int. J. Microwave and Millimeter-Wave Computer-Aided Engineering*, Vol. 7, No. 1, pp. 129–143, Jan. 1997.

[8] C. M. Snowden, "Numerical simulation of microwave GaAs MESFETs", in *Proc. Int. Conf. Simulation Semiconductor Devices Process.* Swansea, U.K.: Pineridge Press, July 1984, pp. 406–425.

[9] K. M. Whight, P. A. Gough and P. Walker, "Large-signal periodic time-domain simulation", *Int. J. of Numerical Modelling: Electronic Networks, Devices and Fields*, Vol. 5, pp. 11–21, 1992.

[10] B. Troyanovsky, Z. Yu and R. W. Dutton, "Large signal frequency domain device analysis via the Harmonic Balance technique", *Proc. of SISDEP*, Vol. 6, pp.114–117, 1995.

[11] F. Filicori, G. Vannini and V. Monaco, "A Nonlinear Integral Model of electron devices for HB circuit analysis", *IEEE Trans. on Microwave Theory & Techniques*, Special Issue on "Process-oriented microwave CAD modeling", Vol.40, N.7, pp.1456-1465, July 1992.

[12] G. Ghione, C. Naldi, F. Filicori, "Physical modeling of GaAs MESFET's in an integrated CAD environment: from device technology to microwave circuit performance", *IEEE Trans. on Microwave Theory & Techniques*, Vol. MTT-37, March 1989.

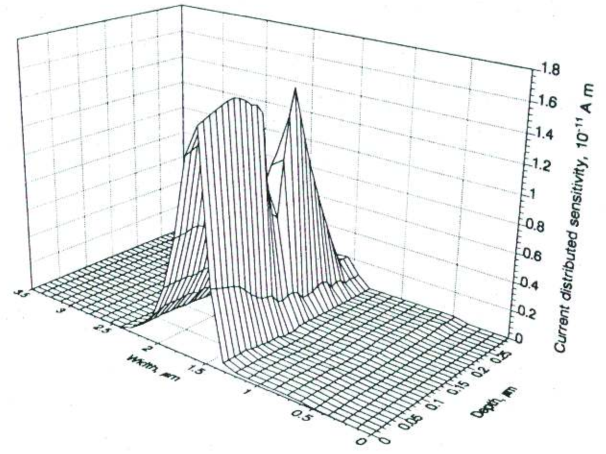

Figure 1: Saturation current distributed sensitivity for a 0.5 μm MESFET. The bias point is $V_{DS} = 3$ V and $V_{GS} = -0.4$ V.

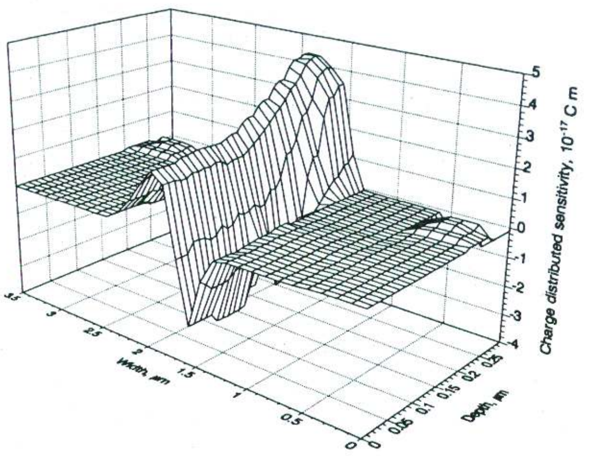

Figure 2: Gate charge distributed sensitivity for a 0.5 μm MESFET. The bias point is $V_{DS} = 3$ V and $V_{GS} = -0.4$ V.

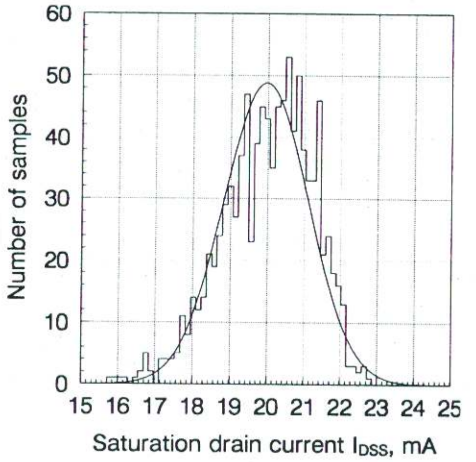

Figure 3: Statistical analysis of the saturation current of a 0.5 μm MESFET. The continuous curve is the sensitivity model, the histogram the distribution obtained through a Monte Carlo analysis carried out directly on the physical model.

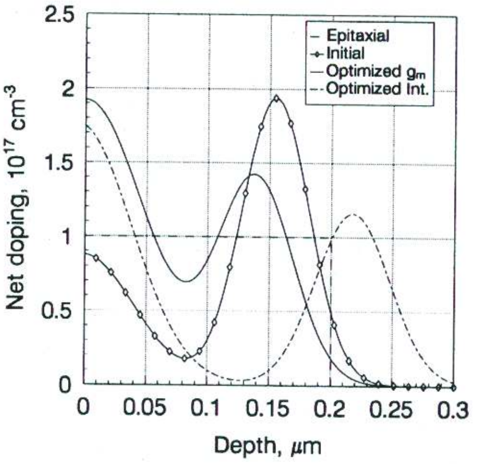

Figure 4: Doping profile for the epitaxial device, the initial two-implant device, the device optimized for maximum linearity and the device optimized to minimize the intermodulation product.

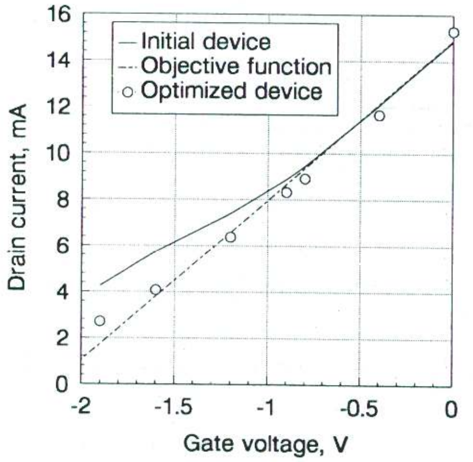

Figure 5: Initial transfer characteristic, final optimized curve and objective function for a 0.5 μm MESFET; a two-implant approximation of the doping profile was used.

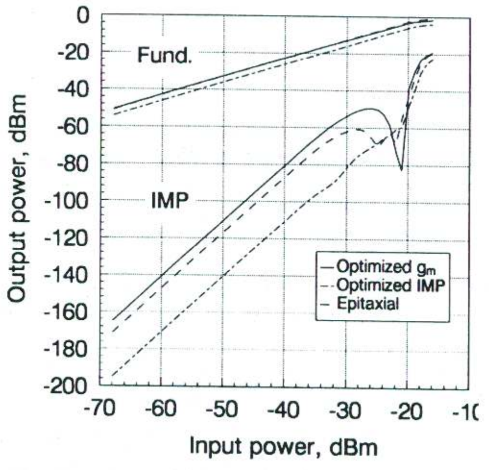

Figure 6: $P_{\rm in} - P_{\rm out}$ characteristics for a two-tone excitation. The two fundamentals ($f_1 = 10$ GHz, $f_2 = 10.1$ GHz), the second harmonic ($2f_1$) and the third order intermodulation product ($2f_1 - f_2$) are shown for the epitaxial, the maximum DC linearity and the optimized (to minimize intermodulation) device.