Physics-based SS and SSLS variability assessment of microwave devices through efficient sensitivity analysis

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***Abstract*—A general framework for the physics-based small-change sensitivity analysis is presented, aimed at the variability assessment of SS and SS-LS device performances as a function of process parameters. The proposed technique is based on the linearization of a physical device model (e.g. drift-diffusion) around a nominal process parameter, and on the evaluation of relevant Green's functions linking the parameter variations in each point of the device to external, circuit-oriented performances, yielding e.g. the sensitivity of the elements of the SS Y parameters and SS-LS $\boldsymbol{Y}$ conversion matrix. This technique allows for a considerable saving of simulation time with respect to repeated incremental analyses.**

***Index Terms*—TCAD sensitivity, SS-LS physics-based analysis**

I. Introduction

Process variability is a serious issue in microwave technologies, especially important in non mature technologies, such as in AlGaN/GaN HEMTs. Various phenomena concur to the total uncertainty of the device performances, the most relevant being the gate length variability due to lateral etching, used e.g. in compound semiconductor FETs to reach nanometer gate lengths; the doping variability; the mobility variability especially in conjunction with thermal stress and crystal damage. Process variability affects microwave subsystems inducing fluctuations in all device performances, including DC, Large Signal (LS) and AC parameters. The major way to address this problem is through the sensitivity analysis: the output performance P undergoes a small variation ΔP induced by a small variation $\Delta\sigma$ of some technological parameter σ, so that in linear approximation, the sensitivity is $S_\sigma^P = \Delta P/\Delta\sigma \approx \partial P/\partial\sigma$. The sensitivity of a total subsystem is obviously linked to the active device sensitivity through standard circuit sensitivity analysis: the active device variability is therefore the critical point to be assessed. In this work we focus the attention on linear or quasi-linear analog blocks, such as LNAs and mixers: typical applications would be assessing e.g. the power/conversion gain or noise figure degradation induced by a combination of transconductance fluctuations and input/output mismatch with respect to the optimum (power/noise) conditions. For these applications, the active device sensitivity is required both in the Small-Signal (SS) and Small-Signal Large-Signal (SS-LS) case. To fully account for accurate technology process variations, device sensitivity is best recovered through physics-based simulations, especially when at the compact model level the link to physical parameters is weak or totally absent. To fix the ideas we will in particular address the evaluation of the sensitivity of the elements of the device SS-LS $\boldsymbol{Y}$ conversion matrix, recovering SS sensitivity as a limit case. Note that the sensitivity of DC parameters such as the drain or collector current is nowadays somewhat established in physics-based analysis [1], [2] also implemented in commercial simulators (e.g., Synopsys SDevice). Instead, the computation of the small-signal parametric sensitivity is in principle a formidable task, since such sensitivities are, in fact, second-order sensitivities of the device short-circuit currents or open-circuit voltages [1]. The problem is mainly due to the need of a "double linearization", one concerning the response of the system to a small electrical signal at frequency f_0, the other to a small variation of a process parameter (obviously to be considered like a "zero frequency" input to the device). In all cases a second order perturbation of either the DC working point (SS sensitivity), or of the LS steady state (SS-LS sensitivity) is required. As a result such analysis has never been presented, not even limited to the SS case.

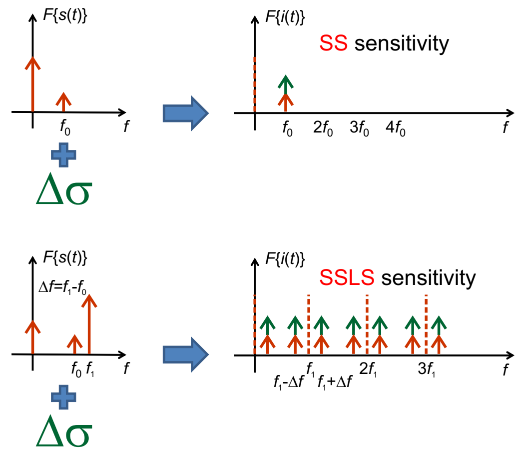

Fig. 1: Schematic representation of the variability modeling approach. $v(t)$ is a terminal applied voltage, $i(t)$ the terminal current, F the Fourier transform.

In the present paper we propose a novel approach to the SS and SS-LS sensitivity analysis that exploits, as a starting point, the LS physics-based model in [3], allowing for harmonic balance based multi tone device simulation including efficient Green's function analysis capability (originally developed for noise simulations). The physical model is first solved without any linearization on the electrical variables, but keeping one of the input tones (at f_0) superimposed to DC or LS (at f_1) so small that the numerical effort required to take this small-amplitude electrical signal into account turns out to be a negligible overhead with respect to the single tone (f_1 only) LS working point evaluation (see Fig. 1). Then the system is linearized to account for the change of the technological parameter, and the variation of the electrical variables is recovered through a Green's function approach. In this way we can circumvent the "double linearization" problem reducing it to a more conventional "single linearization", and keeping the total simulation time comparable to the usual DC or LS working point evaluation. This approach allows us to present preliminary results on the sensitivity analysis of a microwave FET Y matrix.

II. Physics-based SS and SS-LS $\boldsymbol{Y}$ matrix sensitivity

We address the variation of Y parameters (SS case) or the $\boldsymbol{Y}$ conversion matrix (SS-LS) resulting from a given variation of process parameter σ (e.g., the gate length L for geometric sensitivity [4]). In SS-LS the device is driven (see Fig. 1) by a large voltage tone at f_1 and a small input tone at frequency f_0. The simulation is carried out first making an LS simulation with the large tone only. Then the small tone is added exploiting multi tone LS analysis including in principle all mixing terms mf_1+nf_0, where m, n are integers but $n = -1, 0, +1$ only because of the small amplitude assumption. The convergence of the multi tone analysis is extremely fast if the initial condition is the result of the single tone LS working point. To evaluate the conversion matrix, only the output tones with $n = \pm 1$ (sidebands) are used. By denoting as $V_{\pm m}$ the voltage amplitude applied at a given terminal at the sidebands (upper and lower) of mf_1, the corresponding current sideband amplitudes $I_{\pm l}$ (around lf_1) are estimated through the multi-tone simulation. By definition, the Y conversion matrix elements are:

$$Y_{\pm m,\pm l} = \frac{I_{\pm l}}{V_{\pm m}}.$$

Now, the system is linearized to assess the variation of the multi tone LS with respect to σ, and the relevant Green's functions are computed yielding the sensitivity $S_\sigma^{I_{\pm l}}$ of the short-circuit current sideband amplitude with respect to the variation of the parameter σ. Since $V_{\pm m}$ is an impressed voltage undergoing no variation, the sensitivities of $I_{\pm l}$ and of $Y_{\pm m,\pm l}$ are simply related through

$$S_\sigma^{Y_{\pm m,\pm l}} = \frac{S_\sigma^{I_{\pm l}}}{V_{\pm m}}. \quad (1)$$

The SS sensitivity is simply recovered setting $m = l = 0$: in this case the LS preliminary simulation reduces to the customary DC analysis.

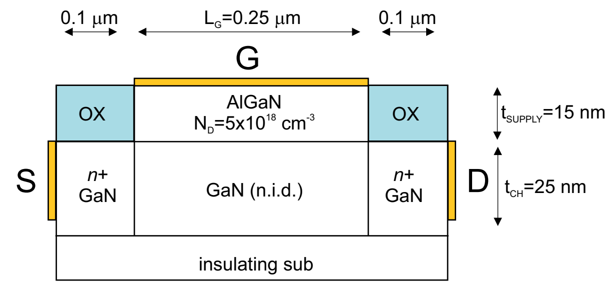

Fig. 2: AlGaN/GaN HEMT device structure.

III. Example

As an example of application, we consider the sensitivity of the Y-parameters of a typical AlGaN/GaN HEMT for high-frequency applications (see Fig. 2 for the structure). The simulation has been performed with a DC bias $V_{\rm GS} = 0$ V and $V_{\rm DS} = 5$ V and an AC tone with 0.1 mV amplitude at 1 GHz, so as to drive the system into a linear AC behavior (SS). The device geometry has been varied by changing the device gate length with steps of 5 nm up to 50 nm, i.e. a total variation up to 20% around the nominal 0.25 μm value. First a reference solution has been found by an incremental approach, i.e. by solving the system with varying gate length. Each time the gate length is varied the device grid is adapted in order to fit the given parameter variation [4]. Then the linearized Green's function approach has been carried out and compared to the reference solution. Finally a standard small-signal AC solution, with linearization around the DC bias point, and repeated analyses with varying gate length values have also been carried out for further reference (incremental SS model). The latter approach turns out to be the most demanding in terms of simulation time. Figs. 3 and 4 show the comparison of the variations of Y_{11} with respect to gate length variations as resulting from the three proposed approaches. The agreement is remarkable especially for gate length variations within 10%, demonstrating the capability of the proposed technique. Figs. 5 and 6 show a similar comparison for the real part of Y_{21} as a function of gate length and supply layer doping variations, respectively. The doping variation was kept within 10% around the nominal value. Again we find an excellent agreement, like for the other Y parameters, not shown for brevity. Physics-based analysis is especially convenient for the extraction of the small-signal equivalent circuit parameters, due to the reduced parasitics (e.g. inductances). From the Y matrix sensitivity, the SS equivalent circuit parameters variability can therefore extracted, yielding a valuable result directly applicable to circuit-level device models. Figs. 7 and 8 show the behavior of $C_{\rm GS}$ and $C_{\rm GD}$ respectively, as a function of the relative percentage variation of both gate length and doping. While the capacitances show a nearly linear variation with respect to gate length as expected, the doping dependency is nonlinear: despite this the Green's function approach is still reliable for doping variation within 5 %.

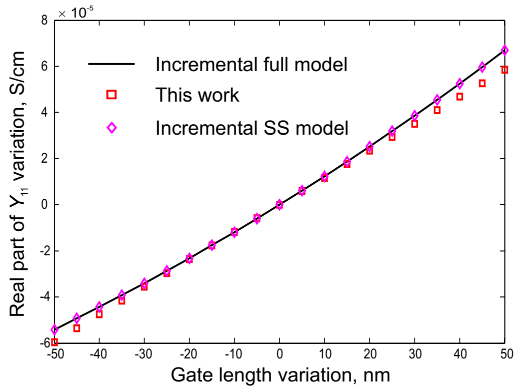

Fig. 3: Y_{11} real part variation as a function of the gate length.

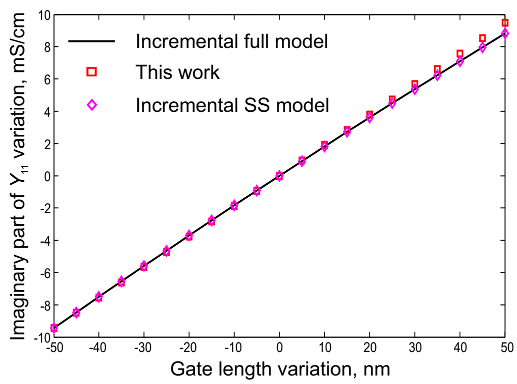

Fig. 4: Y_{11} imaginary part variation as a function of the gate length.

IV. Conclusion

A general framework for the efficient evaluation of SS and SS-LS device small-change sensitivity through TCAD simulation is presented, requiring negligible overhead of simulation time with respect to the nominal device simulation. The variability of the Y matrix of a microwave GaN HEMT device has been presented and validated against other Monte Carlo approaches. The method can be readily applied to the SS-LS Y conversion matrix variability analysis.

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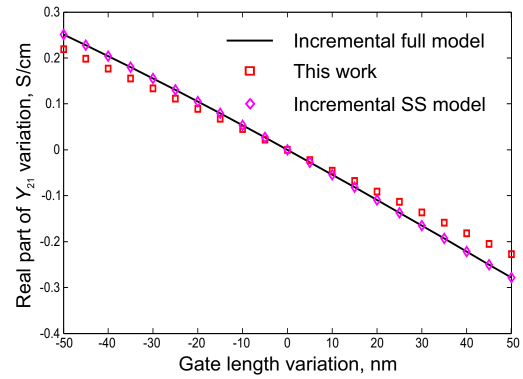

Fig. 5: Y_{21} real part variation as a function of the gate length.

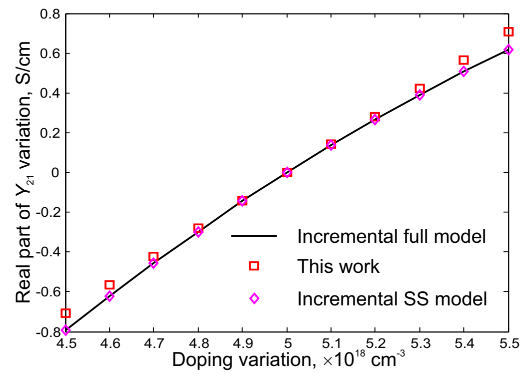

Fig. 6: Y_{21} real part variation as a function of the supply layer doping.

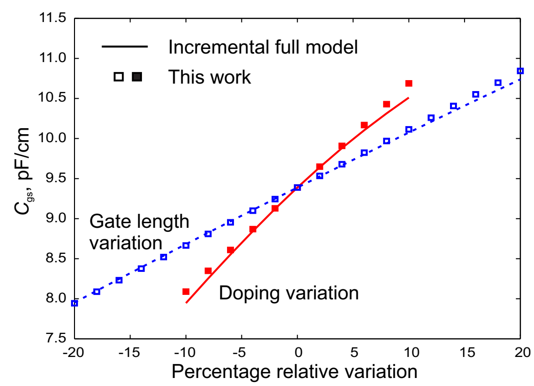

Fig. 7: C_{GS} as a function of the gate length and doping variation.

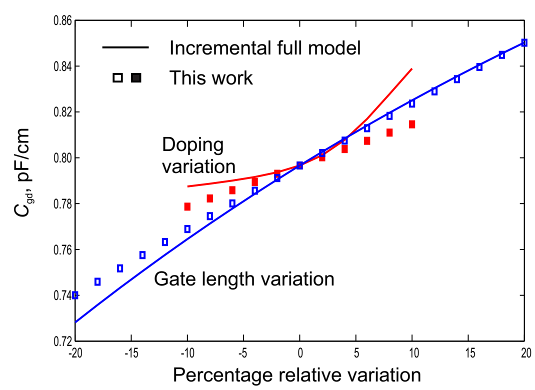

Fig. 8: C_{GD} as a function of the gate length and doping variation.