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Efficient TCAD Large-Signal temperature-dependent variability analysis of a FinFET power amplifier

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Abstract—We present an efficient approach to the temperature-dependent physics-based variability analysis of electron devices in Large Signal (LS) nonlinear conditions. The method extends, with negligible numerical overhead, the Green’s Function (GF) approach, already developed for the device LS noise and technological sensitivity, and allows to calculate the LS device response to the temperature variation from a nominal, “cold” condition with concurrent variations of technological parameters. As a demonstrator we show the T -dependent TCAD simulations of a FinFET-based class A power amplifier against device heating in conjunction with doping variations of the channel contact regions. More than 1 dB output power loss with 50 K temperature heating is demonstrated, while doping variations further affect the PA 1 dB compression point with a 1 dB input power spread.

Index Terms—Semiconductor devices, Nonlinear device models, TCAD simulations, Harmonic Balance

I. INTRODUCTION

Physics-based device simulations represent an ideal environment to accurately model the behavior of the active device in RF/microwave circuits, as they keep trace of the underlying technological and physical parameters and can be easily translated into circuit simulators [1]–[3]. In particular, Large Signal T -dependent analysis is especially relevant in the scenario of power devices (e.g. GaAs or GaN based HEMTs) and nanoscale devices (e.g. FinFETs) [4], [5]. Therefore, to be successfully used for circuit analysis, the physics-based models must be able to predict the *sensitivity* of the nonlinear stage towards 1) technological variations: already addressed in LS conditions by means of Conversion Green’s Functions (CGF) [6], [7]; 2) temperature variations: addressed in [8] through the same CGF; 3) *concurrent* technological and temperature variations: addressed in this work, again through CGF. While coupled electro-thermal simulations are too numerically intensive for LS TCAD analysis, in this work the physical model is parametrized by a unique equivalent temperature T (akin to the “junction” temperature) describing the overall device heating, requiring only T -dependent TCAD LS simulations. Despite being simplified, such an approach is appealing since the LS TCAD electrical model can be further coupled to an external lumped thermal circuit and readily implemented into circuit-level simulators through X-parameters [9]. Our in-house TCAD simulator, allowing for the Harmonic Balance Large Signal analysis of electron devices, along with CGF capability, has been therefore extended to account for

temperature dependency. The CGF approach allows now for the fast and numerically efficient T -dependent LS analysis, starting from a single “cold” simulation, in conjunction with parametric technological variations. In this paper, the novel code is used to simulate a FinFET-based power amplifier (PA) as a function of temperature and concurrent source/drain doping variations, showing that the CGF approach is capable to accurately reproduce the LS stage performance up to 50 K temperature increase, even with a concurrent $\pm 15\%$ doping spread, starting from a single, nominal device simulation.

II. METHODOLOGY

Consider an active device with N -ports connected to an N -port external load, as in Fig. 1. Such scheme represents a general nonlinear circuit, e.g. a power amplifier (PA) where the active device is loaded with proper terminations to maximize the output power (the so-called optimum loads, here represented by the equivalent loads $\mathbf{Z}_L$) and the voltage generators, including the DC bias and the time-periodic sources, represent the external stimuli driving the stage to a nonlinear operating condition. Since the sources are time-periodic, the steady-state operation of the entire system can be represented as a superposition of harmonics for each variable: this is the so-called LS operating regime. In Fig. 1 the device constitutive equations $\vec{f}$ collectively represent a discretized physics-based model (e.g. drift-diffusion), coupled to the external circuit equations of the equivalent loads and power sources [10]. The device and circuit equations form a coupled system:

$$\vec{i}_D = \vec{f}(\vec{v}_D; T, \sigma) \quad (1a)$$

$$\vec{v}_L = \mathbf{Z}_L \vec{i}_L + \vec{v}_0 \quad (1b)$$

where (D) stand for the device and (L) for the circuit (load) terminal variables evaluated in the PA LS working point. The solution must be sought imposing the constitutive equations $\vec{i}_D = -\vec{i}_L$ and $\vec{v}_D = \vec{v}_L$. Such variables are here described in the frequency domain by the corresponding set of harmonic amplitudes (phasors), one for each of the harmonics included in the LS simulation (including the DC component).

Symbols T and σ in (1) represent two parameters influencing the active device operation: respectively, temperature, and one physical parameter (e.g. doping). The LS steady state is calculated with a nominal value σ_0 of the parameter and at nominal (“cold”) temperature T_0 . To efficiently account for a temperature variation δT and any parameter variation $\delta \sigma$, system (1) is linearized around the LS steady-state. Assuming

solution, corresponding to repeated LS analyses with varying T and doping (INC in the figures). As shown in [8], the CGF approach allows a significant reduction of simulation time. In this work with $T = 300, 320, 350$ K and a doping variation of $\pm 15\%$, results show an excellent accuracy of the GF approach in all operating conditions, despite the aggressively reduced simulation time (roughly 17% of the INC analysis). The accuracy of the GF approach is excellent in all conditions, including harsh compression where all the harmonics variations are relevant to the overall performance.

Fig. 4 shows the output power of the PA cell with increasing T , while the available gain with concurrent 20 K T increase and $\pm 15\%$ doping spread in the source/drain regions is reported in Fig. 5. The power performance exhibits more than 1 dB output power loss with 50 K temperature heating. In fact, with increasing temperature, the output power degradation is driven by the mobility reduction and increased source/drain parasitic resistance. The doping variations further affect the same resistances both through mobility degradation and the carrier density spread: hence with higher doping the PA degradation with temperature is milder. The impact of doping is especially significant when the device enters in compression: Fig. 5 shows a 1 dB gain compression point at $P_{\text{disp}} = -7.24$ dBm at $T = 320$ K and nominal doping. At this input power, gain has around 0.3 dB spread due to doping variations. The 1 dB compression point, instead, exhibits about 1 dB P_{disp} spread with doping, with respect to the $T = 320$ K case. The variation of the output power and gain above the 1 dB compression point is mainly due to the knee voltage walk-out with T and doping [15], see the dynamic load lines as a function of T only (Fig. 6), and concurrent T and doping spread (Fig. 7). Notice that the lower the doping, the more the device undergoes early compression, corresponding to lower gain and output power.

Both T and the resistive loss in the source and drain regions affect the stage efficiency considerably. Fig. 8 shows the PA efficiency as a function of the input power: with increasing temperature the efficiency is always less than in the “cold” device due to the combined effect of T degradation and larger parasitic resistances. Doping variations affect efficiency in a more limited way. To highlight their effect, Fig. 9 reports the efficiency variation with respect to the reference solution (i.e., the $T_0 = 300$ K case and nominal doping): at moderate compression (i.e. with $[-14, -8]$ dBm input power), the stage with lower doping is pushed more into compression (see again Fig. 7) and exhibits a higher efficiency with respect to the device with higher doping, which is still in back-off. With increasing compression, though, the stage with lower doping eventually shows an even worse efficiency than the stage with nominal doping due to the higher parasitic resistance.

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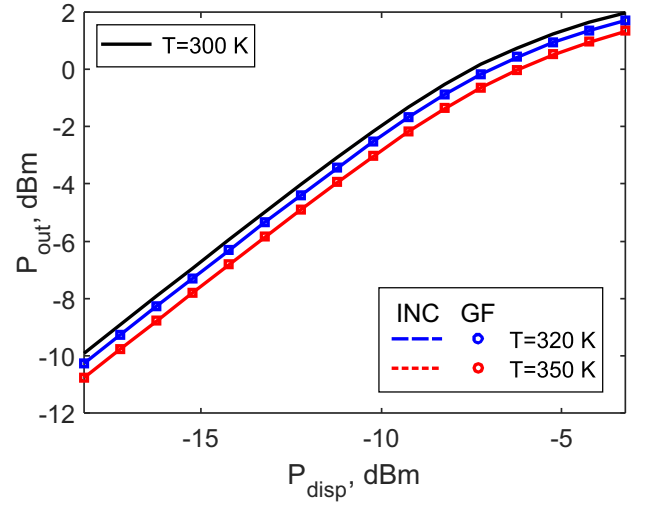


Fig. 4. $P_{\text{in}} - P_{\text{out}}$ plot for the class A PA as a function of temperature.

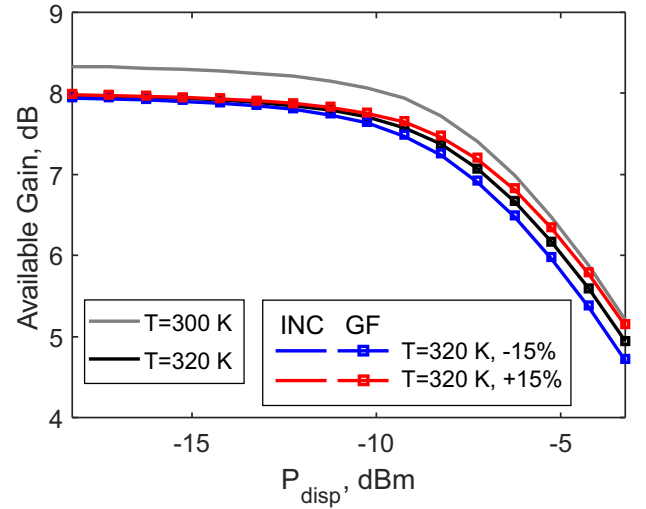


Fig. 5. Available Gain for the class A PA vs. concurrent temperature and doping variations from reference $T_0 = 300$ K solution (grey line).

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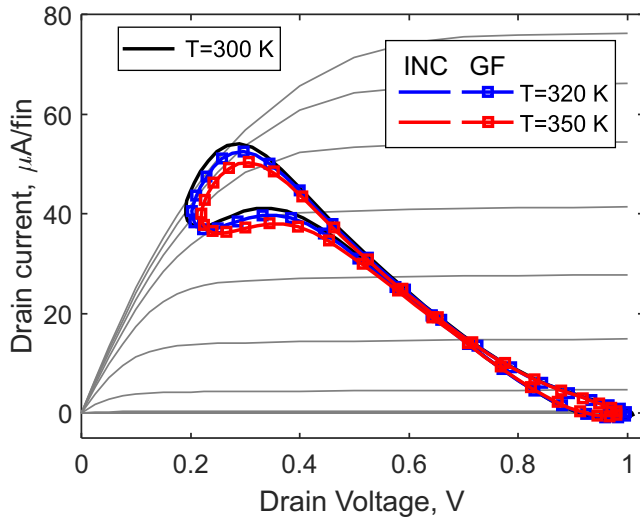


Fig. 6. Dynamic load lines as a function of temperature at 2 dB gain compression ($P_{\text{disp}} = -3$ dBm). Lines: incremental simulations. Symbols: GF approach. Temperature variations from reference $T_0 = 300$ K solution. DC curves are at $T_0 = 300$ K.

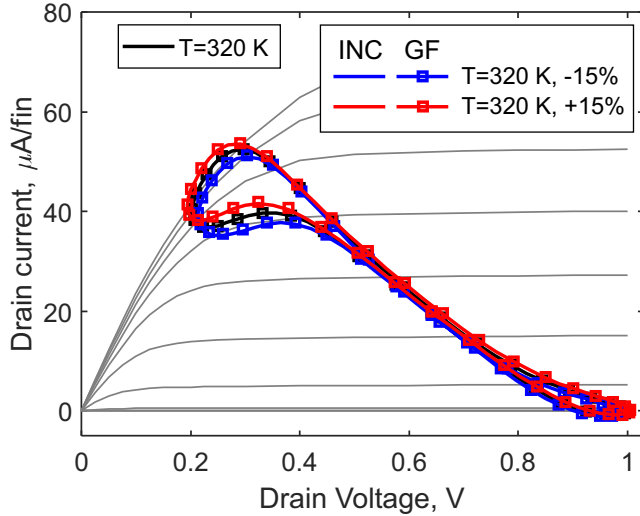


Fig. 7. Dynamic load lines as a function of temperature at 2 dB gain compression ($P_{\text{disp}} = -3$ dBm). Lines: incremental simulations. Symbols: GF approach. Concurrent temperature and doping variations from reference $T_0 = 300$ K solution. DC curves are at $T = 320$ K.

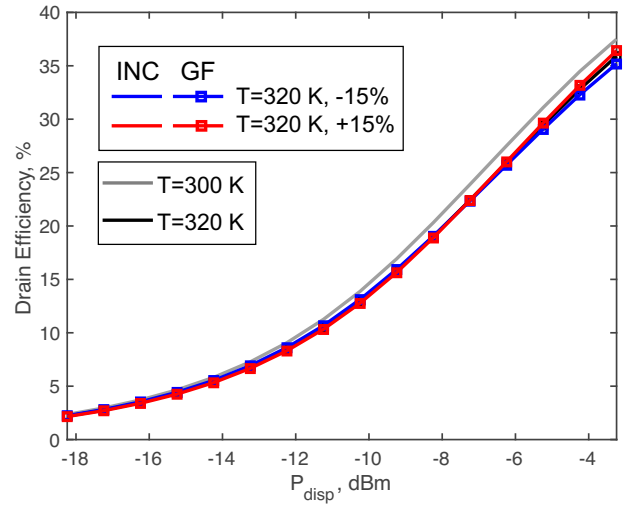


Fig. 8. Efficiency for the class A PA vs. concurrent temperature and doping variations from reference $T_0 = 300$ K solution (grey line).

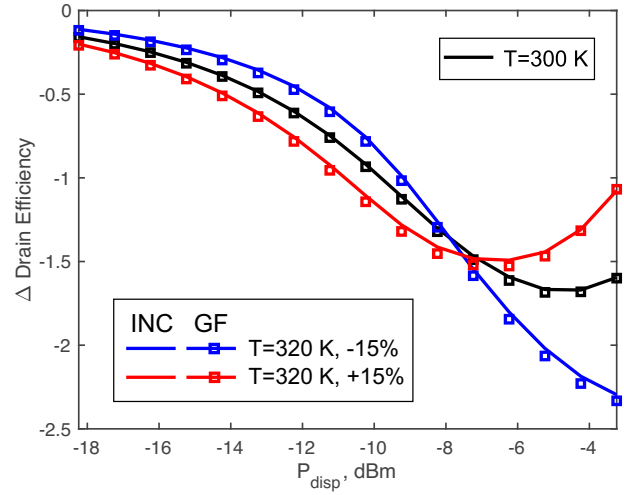


Fig. 9. Efficiency variation with respect to the reference $T_0 = 300$ K solution for the class A PA vs. concurrent temperature and doping variations.

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