Multi-bias Thermal X-Parameter Model for Efficient Physics-Based FinFET Simulation in RF CAD Tools

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Multi-bias thermal X-parameter model for efficient physics-based FinFET simulation in RF CAD tools*

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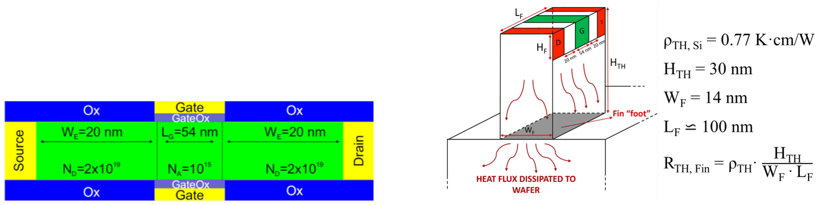
Abstract. In this contribution we present a physics-based multi-bias thermal X-parameter model for a 54 nm Si FinFET transistor. The model is extracted directly in the frequency domain through an in-house developed Technology CAD tool providing Large-Signal analysis using the Harmonic Balance algorithm. Such an approach allows for accurate modeling of parasitic and thermal effects, which are particularly critical in FinFETs, especially in multi-finger devices, due to their peculiar 3D geometry. The X-parameter approach is then exploited to translate the physics-based model into a numerically efficiency parameterized electro-thermal black-box model that can then be adopted for circuit design within EDA tools. Thus, once coupled with an appropriate thermal impedance, it can provide accurate analysis of the device dynamic self-heating. To demonstrate this, we report the analysis of the device, matched at the output for maximum power, at 70 GHz in pulsed mode operation, testing different bias points from class A to class B.

Keywords: X-parameters · Thermal modeling · TCAD · FinFET modeling.

1 Introduction

FinFET technology represents a potential key enabling technology for the integration of RF and digital circuits into a single chip in millimeter-wave phased arrays [12,11]. The peculiar 3D geometry of FinFET transistors, together with the need to use multi-finger structures to achieve proper power levels, calls for accurate physics-based simulations to properly account for all parasitic and thermal effects [13]. This can be effectively addressed by Technology CAD (TCAD) tools embedding Large-Signal (LS) analysis capability. However, TCAD simulations are very time-consuming, while RF designers need reliable and numerically

* Supported by the Italian MIUR under the PRIN 2017 Project N. 2017FL8C9N (GANAPP).



(a) (b)

Fig. 1: FinFET device: (a) 2D cross-section of the fin used for TCAD simulations and (b) fin structure used for the fin thermal resistance calculation.

efficient device models that can be implemented into the commercial RF CAD tools they use for circuit design.

In [7,8] we demonstrated how X-parameters (Xpar) extracted from accurate LS TCAD simulations, can be effectively exploited to obtain an accurate yet efficient parameterized device model, straightforward to be imported into RF CAD tools. The Xpar model can be parameterized as a function of one or more physical (e.g., doping [2]) or electrical (e.g., bias conditions) parameters. Furthermore, temperature (T)-dependent simulations yield a T-dependent Xpar (T-Xpar) model. In this work we present a multi-bias, T-Xpar model of a 54 nm Si FinFET [6], extracted from TCAD LS simulations. The model is adopted to demonstrate a FinFET-based power amplifier (PA) working in pulsed operation, sweeping the bias conditions from class A to class B. The PA self-heating is simulated by coupling the T-Xpar model to a simple thermal-RC circuit.

2 TCAD approach and Xpar model

The adopted TCAD is an in-house developed 2D (planar-3D) drift-diffusion code including different temperature-dependent models [14,10,3,6], e.g. for mobility and thermionic emission in hetero-structures. The developed simulator is able to perform both Large-Signal (LS) and perturbative Small-Signal Large-Signal (SS-LS) simulations exploiting the Harmonic Balance technique and allowing for the X-parameter extraction, as detailed in [7].

The case study is a FinFET device with 54 nm gate-length. The simulated structure is the individual fin, Fig. 1 (a), of a multi-finger device with 10 fingers, each featuring 30 fins of 25 nm height and 14 nm width. LS TCAD analysis was carried out at 70 GHz, with 50 Ω termination at both input and output ports (unmatched), and including 10 harmonics to account for all nonlinearities and to avoid aliasing. The device is assumed isothermal. A temperature-dependent X-parameter model [9,5] was extracted at 2 different gate voltages, namely at 0.675 V corresponding to class A and at 0.5 V corresponding to class B, and at 3 different temperatures, namely 300 K, 340 K and 380 K.

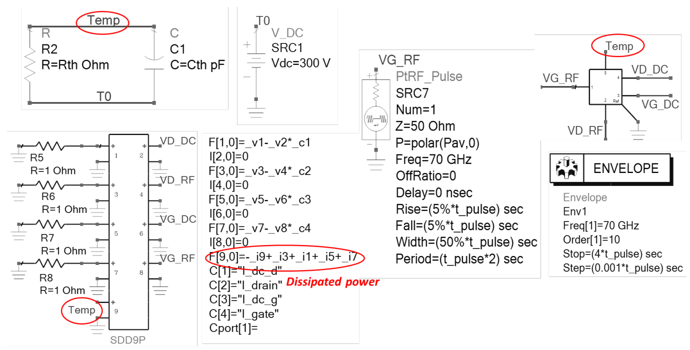
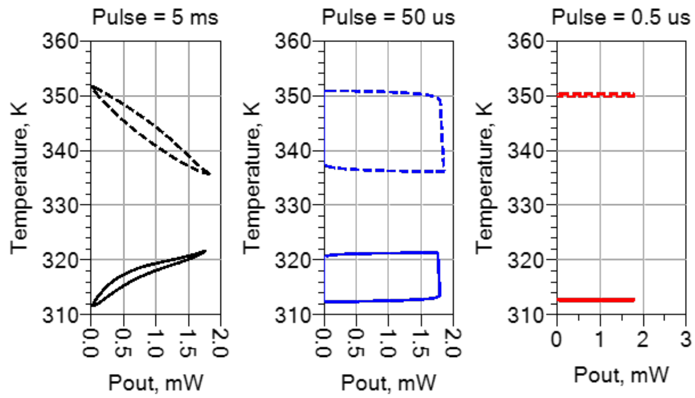


Fig. 2: ADS setup for Envelope PA analysis in pulsed operation.

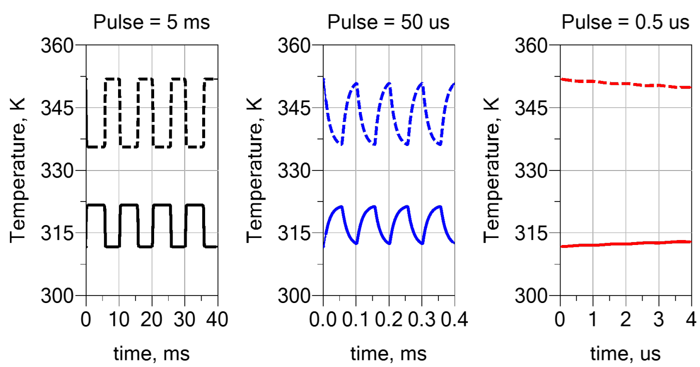
The T-Xpar model is imported into Keysight ADS as an X-parameter file, with a unique gate contact and a fictitious DC voltage port for the temperature, as shown in Fig. 2 [3]. Since X-parameters are instantaneous, for the *dynamic self-heating analysis* [1] the device is coupled to an external lumped RC thermal impedance, through which heat is dissipated towards a heat sink kept at $T_0 = 300\,\mathrm{K}$. The thermal resistance $R_{\mathrm{th}} = 1\,\mathrm{K}/\mu\mathrm{W}$ was calculated paralleling 30 fins, which individual thermal resistance is computed as shown in Fig. 1b, while the thermal capacitance is sized to yield a thermal time constant of $15\,\mu\mathrm{s}$ (10 KHz thermal cut-off). The thermal impedance is used to compute the device temperature as a function of the instantaneous dissipated power through a Symbolically Defined Device (SDDs), which is fed back to the Xpar model to achieve a coupled electro-thermal model, as show in Fig. 2, reporting the simulation set-up: the device input port is terminated on $50\,\Omega$, while the drain port is loaded with the optimum load for power at 70 GHz, $Z_{\mathrm{opt}} = (53 + \mathrm{j}6)\,\Omega$. The bias conditions are varied from class A to class B. The input is pulsed (50% duty cycle, 5% rise/fall time), adopting the Envelope simulation to capture the thermal dynamics.

3 Results

In Fig. 3 we report the analysis of the pulsed power amplifier. When sweeping the gate bias from class A to class B, the available input power is changed to keep the same output power in all cases. Fig. 3-top shows the predicted T vs. P_{out} for 3 different pulse lengths, chosen to be, respectively, below (5 ms), close to ($50\,\mu\mathrm{s}$) and above ($0.5\,\mu\mathrm{s}$) the thermal cut-off, while Fig. 3-bottom shows the temperature variation as a function of time. We can notice the expected opposite behavior of the class A and B stages: the former is hotter when the pulse is off, while the latter gets cooler. The thermal shunt, though, makes temperature variations to be quenched by increasing the pulse speed. Fig. 4 reports the output power variation vs. (normalized) time, highlighting the capability of the T-Xpar model of predicting the P_{out} thermal dispersion. It is worth noticing that this



(a)



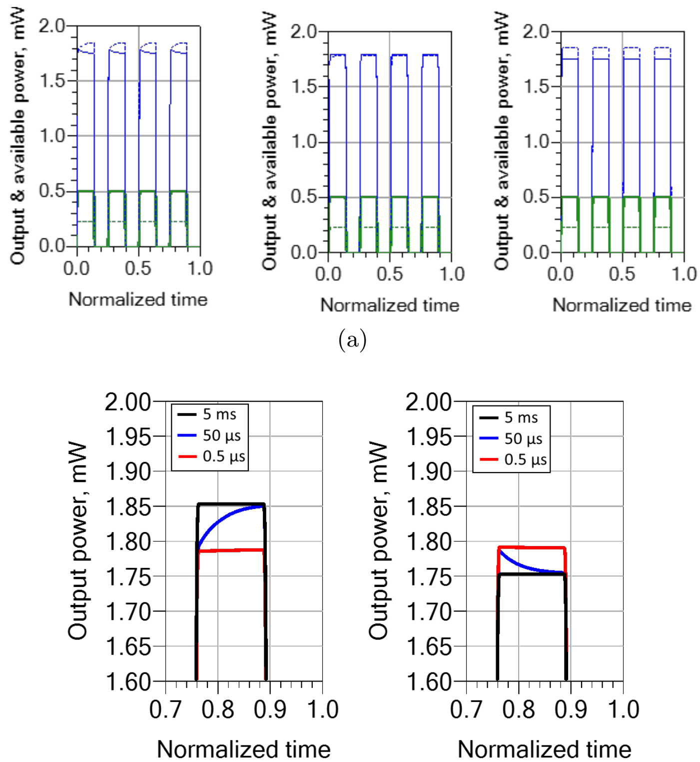
(b)

Fig. 3: Results of the pulsed mode analysis of the matched FinFET in class A (dashed lines) and class B (solid lines): (a) dynamic temperature variation as a function of the output power over the pulse cycle and (b) temperature variation over the cycle for the 3 different pulse durations.

analysis would not be possible adopting a mere X-par model extracted at 300 K. Finally, Fig. 5 shows that the implemented model can continuously interpolate among the X-par data both in terms of temperature and gate bias.

4 Conclusions

An efficient multi-bias thermal model of a 54 nm Si FinFET device is presented. The model is directly extracted from Large-Signal TCAD simulations via the X-parameters approach. The model is then coupled to a thermal impedance to achieve an electro-thermal model capable of predicting the device dynamic self-heating. Exploiting the Envelope analysis, we demonstrated the effect of self-



(b) Class A (c) Class B

Fig. 4: Results of the pulsed mode analysis of the matched FinFET: (a) output power variation over the cycle in class A (dashed lines) and class B (solid lines) and (b) detailed view of the output power behavior in the ON state for the 3 different pulse durations.

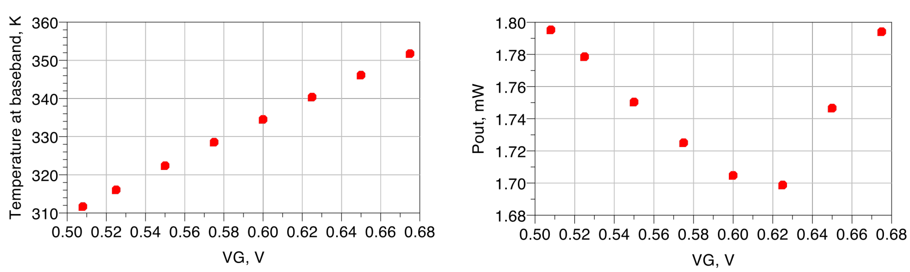


Fig. 5: Results of the pulsed mode analysis of the matched FinFET: (left) temperature at baseband and (right) output power at the RF envelope at different gate bias voltages, from class A to class B, for a pulse length of 0.5 μs.

heating in pulsed operating conditions, highlighting the different role of thermal memory in class A and class B cases.

References

1. Bonani, F., Donati Guerrieri,S., Camarchia, V., Cappelluti, F., Ghione, G., Pirola, M.: When self-consistency makes a difference. IEEE Microwave Magazine. https://doi.org/10.1109/mmm.2008.927638
2. Bughio, A.M., Donati Guerrieri, S., Bonani, F., Ghione, G.: Physics-based modeling of FinFET RF variability. Eu. Microw. Integrated Circ. Conf., EuMIC 2016. https://doi.org/10.1109/eumic.2016.7777534
3. Catoggio, E., Donati Guerrieri, S., Bonani, F., Ghione, G.: Efficient TCAD temperature-dependent large-signal simulation of a FinFET power amplifier. Eu. Microw. Integrated Circ. Conf., EuMIC 2021. https://doi.org/10.23919/eumic50153.2022.9783235
4. Catoggio, E., Donati Guerrieri, S., Bonani, F., Ghione, G.: TCAD-based Dynamic Thermal X-parameters for PA Self-Heating Analysis. Accepted for presentation at Eu. Microw. Integrated Circ. Conf., EuMIC 2022.
5. Catoggio, E., Donati Guerrieri, S., Ramella, C., Bonani, F.: Thermal modeling of RF FinFET PAs through temperature-dependent X-parameters extracted from physics-based simulations. Int. Workshop Integrated Nonlinear Microw. Millimetre-Wave Circ., INMMiC 2022. https://doi.org/10.1109/INMMiC54248.2022.9762142
6. Catoggio, E., Donati Guerrieri, S., Bonani, F.: Efficient TCAD thermal analysis of semiconductor devices. IEEE Tran. Electron Dev. (2021). https://doi.org/10.1109/ted.2021.3076753
7. Donati Guerrieri, S., Bonani, F., Ghione, G.: Linking X parameters to physical simulations for design-oriented large-signal device variability modeling. IEEE Int. Microw. Symp., IMS 2019. https://doi.org/10.1109/mwsym.2019.8700869
8. Donati Guerrieri, S., Ramella, C., Bonani, F., Ghione, G.: Efficient sensitivity and variability analysis of nonlinear microwave stages through concurrent TCAD and EM modeling. IEEE J. Multiscale Multiphysics Computational Tech. (2019). https://doi.org/10.1109/jmmct.2019.2962083
9. Gillespie, S.J., Root, D.E., Marcu, M., Aaen, P.H.: Electrothermal X-Parameters for dynamic modeling of RF and microwave power transistors. Eu. Microw. Integrated Circ. Conf., EuMIC 2018. https://doi.org/10.23919/eumic.2018.8539893
10. Prasad, C.: A review of self-heating effects in advanced CMOS technologies. IEEE Tran. Electron Dev. (2019). https://doi.org/10.1109/ted.2019.2943744
11. Raskin, J.P.: FinFET versus UTBB SOI — a RF perspective. Eu. Solid State Dev. Research Conf., ESSDERC 2015. https://doi.org/10.1109/essderc.2015.7324719
12. Scholten, A., et al.: Experimental assessment of self-heating in SOI FinFETs. IEEE Int. Electron Dev. Meeting, IEDM 2009. https://doi.org/10.1109/iedm.2009.5424362
13. Uchida, K., Takahashi, T.: Thermal-aware CMOS: Challenges for future technology and design evolutions. Eu. Solid-State Dev. Research Conf., ESSDERC 2016. https://doi.org/10.1109/essderc.2016.7599609
14. Venkateswarlu, S., Sudarsanan, A., Singh, S.G., Nayak, K.: Ambient temperature-induced device self-heating effects on multi-fin si n-FinFET performance. IEEE Tran. Electron Dev. (2018). https://doi.org/10.1109/ted.2018.2834979