

Empirical and Physical Modeling of Self-Heating in Power AlGaN/GaN HEMTs

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Self-heating is among the most significant performance and reliability limiters for power devices and circuits. GaN-based HEMTs, today's most promising technology for microwave PAs, but rapidly emerging among high-power switches, too, are a case in point, since exploiting to the fullest the outstanding material properties necessitates thermal aspect to be carefully addressed in device design and manufacturing, as well as in reliability estimation. While Finite Element (FE) simulation is a powerful physical modeling approach able to deal with large 3D structures made of different materials (with temperature-dependent thermal conductivities), and including top- and back-side features and thermal boundary conditions not to be overlooked, FE models can be computationally heavy and cannot be integrated in comprehensive design suites, unlike lumped-element (LE) models. In previous works, we proposed a hybrid approach, whereby LE 2D [1] or 3D [2] thermal networks representing physical models of the device stack are coupled with large-signal electro-thermal HEMT models for self-consistent simulation of the device DC and RF behavior including self-heating. This technique was proven to be accurate enough, but becomes cumbersome for complex structures like large-periphery HEMTs for PAs, and when top metal lines and pads, as well as via holes etc., are to be included in the thermal model.

Here we explore two ways of overcoming this difficulty: (1) empirical RC network LE modeling (e.g., [3]); (2) simplified physical LE modeling, following [1], [2]. We use FE simulation to validate the LE models.

Fig. 1 shows the HEMT structure we use as a test bench: it is the basic building block of a much larger power HEMT; the whole HEMT can be thought of as a periodic repetition of such blocks. Fig. 2 shows a blow-up of the HEMT surface, where the thin (blue) gate fingers can be discerned. The block is made of 5, 200 μm wide fingers (where heat is generated), abutting interdigitated source/drain regions. Metal lines and a source via hole are included in the model, as well as the bottom die-attach layer, as shown in Fig. 1. We consider the case of Si substrate. GaN and Si thermal conductivities are temperature-dependent [4]. Details of the structure geometry and material properties will be given in the full paper. Fig. 3 shows an example of FE thermal simulation.

(1) *Empirical LE modeling* – We first try to model the dynamic self-heating behavior of the structure in Fig. 1 using a Foster RC thermal network (Fig. 4, top). We start from the FE-simulated temperature response to a dissipated power step, which is fed to an algorithm that extracts a rough estimate of the relevant time constant from the peaks of the $dT/(d(\ln(t)))$ response [3] (T being the temperature of the hottest spot, while t is time); an optimization algorithm then gets rid of the irrelevant time constants and fine-tunes the relevant ones. An example of results is shown in Fig. 5. The automated algorithm extracts 4 time constants, 2 of which are very similar, so the optimized Foster network has 3 RC stages, with $\tau_1 = 5.1 \mu\text{s}$ ($R_{\text{TH1}} = 52.2 \text{ K/W}$, $C_{\text{TH1}} = 9.77 \times 10^{-7} \text{ J/W}$), $\tau_2 = 45.2 \mu\text{s}$ ($R_{\text{TH2}} = 48.3 \text{ K/W}$, $C_{\text{TH2}} = 9.36 \times 10^{-7} \text{ J/W}$), $\tau_3 = 438 \mu\text{s}$ ($R_{\text{TH3}} = 156 \text{ K/W}$, $C_{\text{TH3}} = 2.81 \times 10^{-6} \text{ J/W}$). It is to be noticed that this approach yields a purely empirical model, where thermal R 's and C 's cannot be given a true physical meaning; it is also worth pointing out that the FE simulation features T -dependent thermal conductivities for GaN and Si. This simple example shows the LE Foster network approach to be able of replicating the thermal step response with very good accuracy with as few as 3 RC stages. The final paper will expand the analysis by: (a) modeling the T response of device locations other than the hottest spot (Fig. 5), to account for 2D surface T non-uniformity; (b) modeling the T response in the case of different top-side heat sinking conditions (in the case of Fig. 5, heat is dissipated only via the bottom of the die, fixed at 300 K); (c) converting the extracted Foster networks into more physics-based Cauer RC networks (Fig. 4, bottom), and compare the thermal R 's and C 's of the Cauer network with the physical characteristics of the HEMT: it is of interest to understand how much physical information can be retained in a network as simple as that in Fig. 4b.

(2) *Physical LE modeling* – We first tried to approach the thermal modeling of the 3D structure of Fig. 1 with a 2D network of thermal R 's and C 's physically representing the cross section of the HEMT orthogonal to the finger width and passing through the finger center, i.e., the hottest 2D cross section. The network is in this case of the kind shown in [1], with building blocks of thermal R 's and C 's simulating volume elements of the physical structure, and directly calculated from material properties and from the element's dimensions. However, in spite of the large width of the fingers (200 μm), the thermal flow from surface to bottom is far from being 2D, and the 2D LE model yield errors in the range of 100%, since it represents a worst-case adiabatic condition for the central cross-section of the HEMT. The full paper will elaborate more in this direction, too, with the goal of developing the simplest possible (2D or quasi-2D) physical LE model capable of retaining the core information necessary for accurate electro-thermal device modeling.

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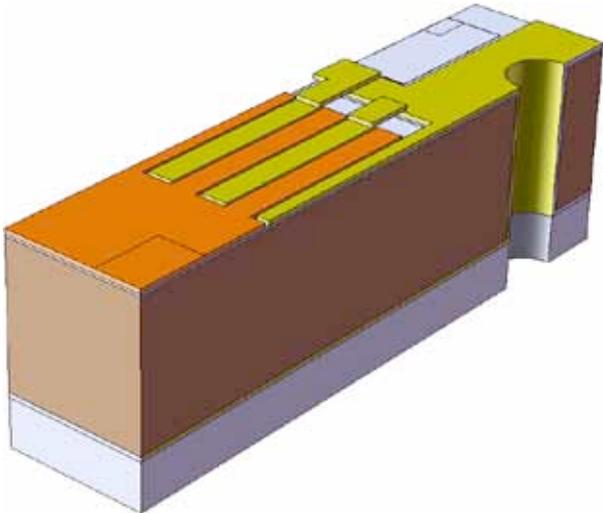


Fig. 1 The modeled structure, representing the building block of a large-periphery power AlGaIn/GaN HEMT.

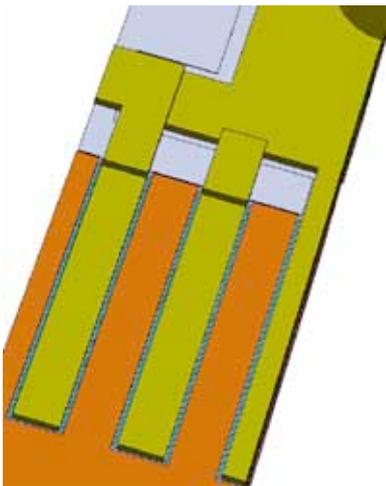


Fig. 2 A blow-up of Fig. 1.

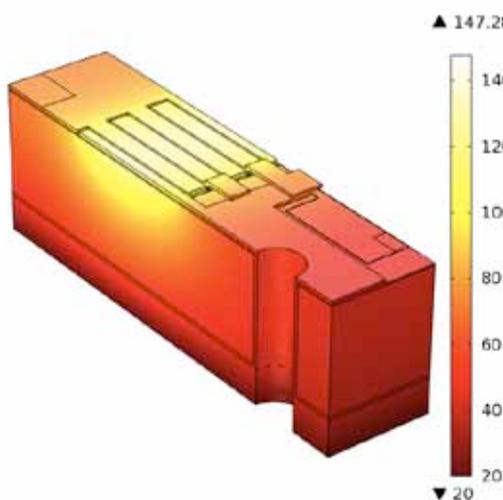


Fig. 3 FE thermal simulation of the structure of Fig. 1.

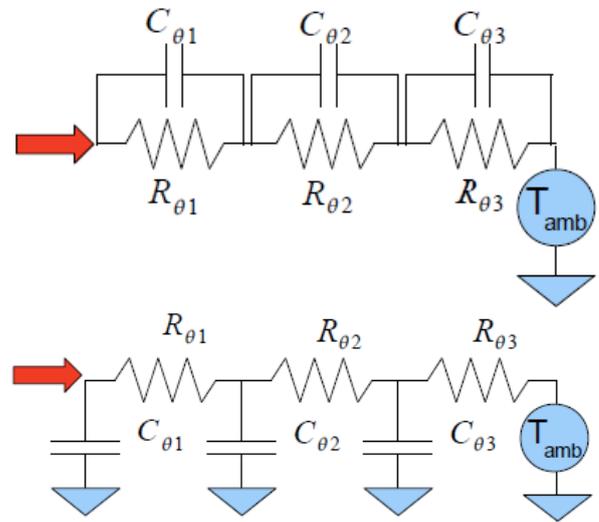


Fig. 4 Foster (top) and Cauer (bottom) 3-stage LE thermal networks.

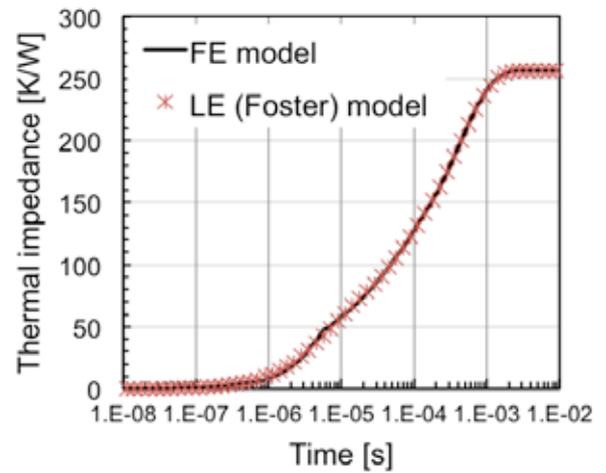


Fig. 5 Thermal impedance ($\Delta T(t)/P_D$) of a HEMT finger following a power step of $P_D = 0.5$ W/finger, as given by the FE simulation and the empirical LE Foster RC network with 3 time constants. The temperature is that of the hottest spot of the HEMT.