GaN HEMTs for Power Switching Applications: from Device to System-Level Electro-Thermal Modeling

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While still expanding in the microwave arena, GaN-based HEMTs are increasingly making their way into the field of high-power switching thanks to the material's advantages in terms of power handling and switching frequency capabilities [1]-[6]. Since high-power applications demand particularly strenuous attention to thermal considerations, thermal modeling of GaN-HEMTs has attracted more and more attention over the last few years, with implications on device design and manufacturing [7], [8], electrical performance [9]-[11], reliability [12], packaging and cooling strategies [13], etc., but mostly in the field of microwave applications and MMICs.

However, power converters are complex, hybrid systems, and thermal modeling cannot be confined to the device domain: on the contrary, it has to cover all domains, from the device to the package, the heat sink, and finally the board or boards on which the switches are assembled with passive components, freewheeling diodes, etc. This global approach to thermal modeling is not commonly seen, but as different companies enter the market of GaN-based switching converters, it will have to be increasingly seen as a critical tool for manufacturers and users.

Over the years, our group developed extensive experience in this field, and reported thermal modeling methodologies and results spanning all the way from the device physical level [7], [8], [14] to circuit-level compact electro-thermal (ET) models [9], [10], power MOS device-package modeling [15], and DC-DC converter system-level thermal modeling [16], [17]. This work aims at applying this range of modeling and characterization techniques to GaN high power switches and the circuits using them.

The first step in the thermal and electro-thermal modeling and characterization process focuses on the semiconductor die. Here all available information on device geometry and physical structure, material properties, etc., can be used to develop a physical thermal model of the die or, much more frequently, since the whole device layout always has a modular, interdigitated and symmetric structure, of a basic cell that represents the elementary building block the switch is made of. At this level, thermal modeling is generally and most efficiently carried out using Finite-Element (FE) tools. An example of FE simulation, showing the DC thermal map of the 5-finger basic cell of a much larger GaN HEMT switch die, is shown in Fig. 1. Top metal lines and pads, source via hole, and die attach layer are included in the model.

Simulations like that of Fig. 1 are extremely useful not only in the device design phase, but also as a guide for the development of the compact models that will be used in circuit-level simulations. As an example, it is found that temperature can hardly be considered uniform along each gate finger, as shown in Fig. 2. The concept of a single channel temperature is therefore questionable at best. Our choice in the development of an ET model was therefore to partition the structure along the gate finger width into five 40 μm-wide sections (A-E, Fig. 2). Each of these sections is associated with its own channel temperature and an independent ET model can thus be extracted and used for accurate description of the HEMT behavior.

A Lumped-Element (LE) thermal model can be extracted from the FE-simulated or from the measured thermal dynamics of the HEMT, using known algorithms [14]. An example of the match between FE and LE thermal models is in Fig. 3. Once an accurate LE thermal model is available for each of the basic cell sections A-E, the thermal LE networks can be inserted in a self-consistent feedback loop such as that shown in Fig. 4 for physics-based circuit-level ET simulation of power converters.

The complex thermal interactions among the components the whole converter is made of can finally be studied by 3D FE simulations (Fig. 5) and infra-red thermography (Fig. 6).

The extended abstract will show details of the application of this general procedure to the specific case of a commercial power GaN HEMT switch and a GaN-HEMT-based power converter. Experimental results will be used for model extraction and validation.

References

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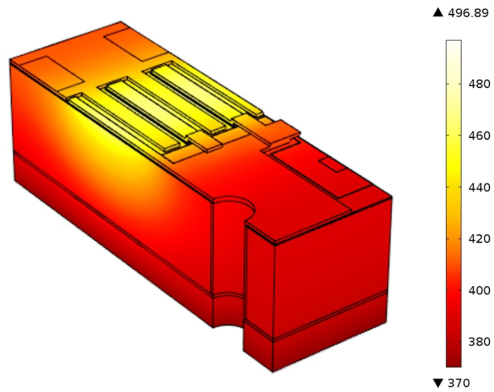

Fig. 1 FE thermal simulation of the basic cell (5x200 μm) of a large-periphery power AlGaN/GaN HEMT switch. The back-side temperature is fixed at 370 K. The dissipated power density per unity gate width is 2.5 W/mm.

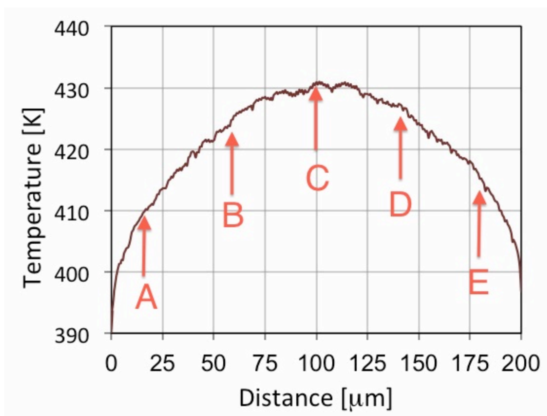

Fig. 2 FE-simulated temperature along the 200 μm width of a GaN HEMT. P_D = 2.5 W/mm. Distance is measured from the finger edge closest to the source via hole. The arrows mark the points used for the extraction of the LE thermal networks. The back-side is at 300 K.

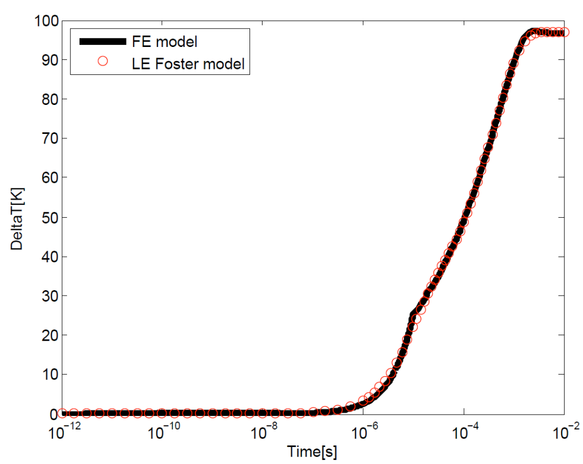

Fig. 3 Comparison between FE and LE simulation of the temperature increase in the A section (Fig. 2) of the HEMT switch cell of Fig. 1 following a power step of 2.5 W/mm. The LE model is a 3-stage Foster RC network [14].

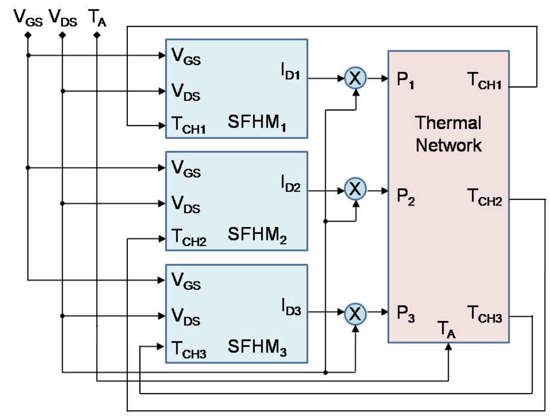

Fig. 4 Self-consistent electro-thermal feedback loop for circuit-level simulation of the GaN power switch. Only 3 sections are shown instead of the 5 in Fig. 2, for the sake of simplicity. SFHM is a large-signal temperature-dependent HEMT model. The Thermal Network is made of 3 (5 in the real case) LE Foster or Cauer [14] RC thermal networks.

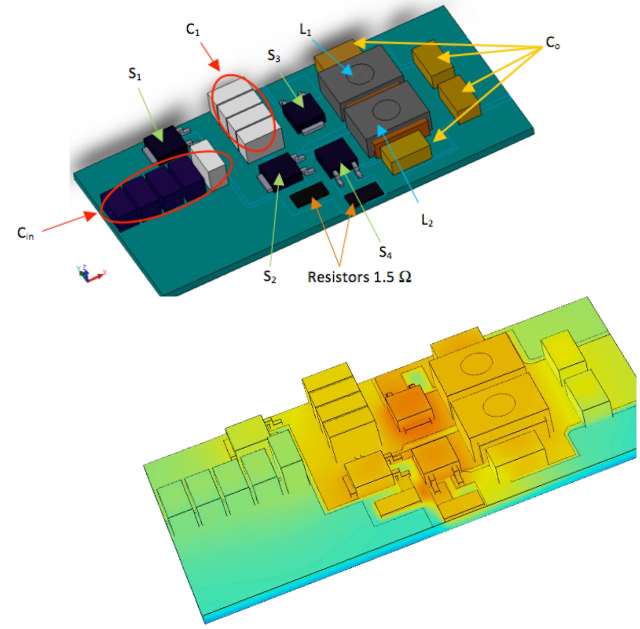

Fig. 5 An example of 3D FE thermal simulation of a DC/DC power converter board.

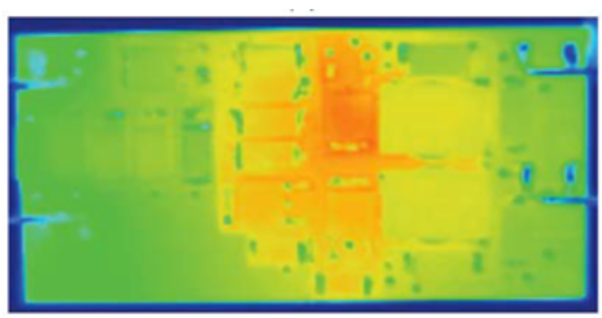

Fig. 6 Infra-red thermography map of the DC/DC power converter board simulated in Fig. 5.