Modeling Needs for Power Semiconductor Devices and Power Electronics Systems

Preprint

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National Renewable Energy Laboratory

Presented at 2019 IEEE International Electron Devices Meeting (IEDM)
San Francisco, California
December 7-11, 2019

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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Contract No. DE-AC36-08GO28308
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Suggested Citation

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Modeling Needs for Power Semiconductor Devices and Power Electronics Systems

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Abstract—As energy systems move towards wide-spread electrification, penetration of power semiconductor devices and power electronics continue to grow at a rapid pace. This paper attempts at reviewing the state-of-art in power semiconductor modeling and the existing state of modeling in general when it comes to design of devices and systems. The modeling needs for semiconductor devices vary depending on the end-goal and the level of abstraction needed towards model formulation also changes with the size and complexity of system to be designed. Finally, key aspects of thermal design and modeling for power electronics is also discussed.

I. INTRODUCTION

Power Electronics systems are increasingly becoming prevalent in the changing landscape for modern energy systems [1]. At the heart of power electronics systems are power semiconductor devices that enable the energy conversion from source side to the loads. The modeling field in power semiconductor devices has not been fully matured when compared with analog and digital semiconductor devices and is still evolving to adapt to recent disruptions in power electronics caused by the penetration of wide band-gap devices (WBG) [2]-[5]. The major challenges being faced towards modeling of power semiconductor devices stems from the fact that power electronics systems are very diverse and the complexities very from a simple dc-dc energy conversion topology to a complex system such as a grid-tied power electronics interface or a standalone microgrid for distributed generation. In such cases, it becomes extremely difficult to standardize on the modeling approaches for power semiconductor devices.

II. MODELING NEEDS FOR POWER SEMICONDUCTOR DEVICES AND EMERGING WIDE BANDGAP DEVICES

A. Device Design Needs

Wide bandgap devices have come a long way in power electronics since the first SiC devices were demonstrated. The process development and fabrication of power semiconductor devices for new material is an extremely challenging task due to the lack of information on characterization of material and its performance. Finite element modeling in semiconductor devices has largely become possible due to commercial technology computer aided design (TCAD) tools such as Sentaurus and ATLAS Silvaco [7]. There are some open source TCAD tools like DEVSIM also available for device design. These tools are mainly based on the solutions of carrier transport equations as a function of lattice temperature. Regardless, TCAD modeling is highly suitable for process and device design and may not be suitable for circuit or system simulations. Fig. 5 shows the results obtained for a TCAD model developed for Ga2O3 devices.

B. Modeling for Circuit Design and System Simulation

While finite-element models are an attractive choice for device design, they are practically impossible to use for circuit and system design. The modeling needs for circuit design require that the semiconductor models are in their compact form and represent 1-D representation of the higher-order effects. Also, the models should be parameterized in a way that the parameters can be easily extracted from the measured device characteristics. The key device characteristics such as dc IV, CV, gate charge, and thermal impedance are usually needed to characterize a model suitable for circuit and system design simulations.

Semiconductor models represent different levels of abstraction depending on the end-goal (Fig. 1 and 2). E.g., if the goal is to evaluate a device just for its switching characteristics, a compact model with detailed channel current and charge equations must be used such that the parameters of the model can be easily extracted from the measured device characteristics as shown in Fig. 3. A detailed model which is physics-inspired is likely to capture the overall switching and conduction losses and is also more likely to accurately predict the frequency response as well as time-domain behavior resulting from interactions between device and circuit parasitics (Fig. 4).

As a result, a wide range of power electronic systems are now way more complex than a simple switching converter. A lot of system level designs require simulation engines like MATLAB/Simulink® and PLECS. A complex switching device model may consume a lot of computing resources when used in complex system-level designs for simulations. As a result, tools like MATLAB/Simulink® and PLECS have become very popular wherein the semiconductor switches, although not ideal, do not represent the same level of complexities as behavioral or physics-inspired models would represent [8].

As a result, modeling needs continue to evolve and adapt to the changing landscape of evolving energy systems. The complexity of any given model largely depends on the level of abstraction made from its actual physical behavior. And the levels of abstraction are usually determined depending on the end-goal of the model. The higher the level of abstraction, more physical in nature the model is. Thus, the choice of complexity of the model is need-based and the availability of software tools as well as computing resources. A complex model is likely to consume more computing resources and simulation time. Thus,
Numerous software programs provide semiconductor switch models for power electronics design and simulation that blends with their simulation engines. The models are mostly behavioral or sub-circuit-based and are usually not scalable to physical and process parameters. Recently, OnSemi has started to roll out SPICE models for its power device products that are claimed to be physically scalable and directly tied to the process device parameters [6]. The power MOSFET model captures device electro-thermal behavior with athermal impedance network that calculates device junction temperature ($T_j$) to characterize the effect of device self-heating on device transient performance. The model is demonstrated as scalable to process parameters. The channel current is modeled by BSIM3 model equations which requires further research because the device structure presented in the model is representative of a VDMOS device while the BSIM models are primarily for low voltage lateral MOSFET devices used in IC designs. Nevertheless, the effort to standardize modeling approaches for power semiconductor devices is in the right direction considering the challenges posed by emerging WBG devices.

### III. THERMAL MODELING IN POWER ELECTRONICS

Most automotive power electronics are cooled using a liquid (water-ethylene glycol solution) heat exchangers (Fig. 6). Some of the early inverter designs used a cold plate cooled configuration that mounted the power module to an aluminum cold plate with thermal grease at the interface. More recent inverter-designs now use a baseplate cooled configuration which eliminates the thermal grease (largest thermal resistance component) and directly cool the baseplate. Double side cooled modules are also an effective method to further improve thermal performance by removing heat from both sides of the module. The double side cooled approach is becoming more common with the advent of planar package designs that eliminate the wire bonds. Designing the convective cooling systems requires knowledge of the operating conditions. Computation fluid dynamics (CFD) methods can be used to design the fluid flow path and surface enhancement features (e.g., fins, coatings). Finite element (FE) methods can be used to compute the junction temperatures using the CFD-estimated convective heat transfer coefficients. Steady-state and transient thermal simulations can be conducted using the simpler FE models to evaluate various operating conditions.

**REFERENCES**


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Figure 1. (a) Representative 2-D device structure of a vertical power MOSFET device.

Figure 1. (b) Equivalent circuit representation in device’s large signal topology.

Figure 2. (a) Representative 2-D device structure of an IGBT device.

Figure 2. (b) Equivalent circuit representation in device’s large signal topology.

Figure 3 Model Characterization for 1-D SPICE models of GaN power devices
Fig. 4(a) On-state behavior of a device characterized in a switch-mode circuit

Fig. 4(b). Off-state behavior of a device characterized in a switch-mode circuit

Fig. 5 TCAD Modeling results for the Ga₂O₃ planar power MOSFET device, including (a) transfer characteristics for different Mg doping levels, with logarithmic plot in inset, and (b) dc output characteristics for different gate voltages

Fig. 6. Typical liquid-cooled power module configurations, cold-plate cooled (left), baseplate cooled (middle), and double-sided cooled (right)

ACKNOWLEDGMENT
This work was authored by the National Renewable Energy Laboratory (NREL), operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. This work was supported by the Laboratory Directed Research and Development (LDRD) Program at NREL. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.