Power Semiconductor Device Modeling and Simulation

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The educational efforts at the University of Arkansas in the area of power semiconductor device modeling and simulation are described. The past two decades have seen tremendous strides in silicon (Si), silicon carbide (SiC) and gallium nitride (GaN) power semiconductor device developments. It is important that power electronics students understand the capabilities and limitations of various device technologies in order to design and build circuitry that can meet performance specifications at minimal cost.

The UA program integrates research projects, coursework, and supplemental tutorials to achieve its educational mission in devices. This material is provided in such a way that the learning process does not have to be sequential. Graduate students are often required to begin their research projects before they have had a chance to enroll in some of the relevant courses. Thus, as often as not, the process may begin with self-guided tutorials captured on wiki pages and required reading from key books and articles.

Wiki-based tutorials include information on device modeling, parameter extraction, and circuit simulation. Students are able to read through these tutorials and begin to understand how models are constructed, how certain software is used to optimize the model to measured data, and how to deploy models in a simulator for subsequent circuit analysis. Seminal books and articles that describe principles of operation for Si, SiC, and GaN devices are either available on the wiki site or referenced there, so that the student can begin to gain a physical understanding. Additional tutorial information on performing finite element device simulation for electrical and thermal analysis is available to enhance this understanding. Lastly, tutorials on device measurements are available such as testing with a high power, high temperature probe station along with making switching and device capacitance measurements.

The first course is a graduate course on power semiconductor devices. The learning objectives of the course are:

- Learning the physics and principles of operation of several commonly used power semiconductor devices
- Learning how power devices differ from low-voltage, microelectronic devices (there is a prerequisite course on Semiconductor Devices taught from Streetman [1])
- Learning both Si and SiC material properties and power device technologies associated with each material

The course is taught from a collection of course notes developed through the years, and uses three reference books by Ghandi and Baliga [2]-[5]. The course first covers power electronic applications that motivate the use of different devices in various settings. This is followed by a treatment of basic material properties of silicon and silicon carbide including lattice structures, mobilities, bandgap considerations, thermal properties, and typical doping characteristics. The bulk of the course focuses on power device types from diodes to field effect devices to bipolar devices. As each device type is treated both silicon and silicon carbide devices are described. A few lectures are devoted to computer-aided device analysis using tools such as Synopsys' Taurus-Device. Finally, the course culminates with a discussion of alternative materials for power devices including GaN, SiGe, and diamond. This course does not have a laboratory component, but measurement data from most of the devices presented is available to illustrate the performance features of the device.

The UA's research program has developed new compact models for a number of Si and SiC devices [6]-[9]. This ongoing device modeling research activity is integrated with power electronic circuit design activity to ensure progress in both areas. Each device modeling project feeds new information back into the course and wiki pages so that all of the material is kept current and relevant. A couple of these projects will be described in the full paper to illustrate the feedback of research results into the "classroom".

In general, students learn a variety of important aspects about power devices in this course. Among these are: trade-off between on–state resistance and breakdown voltage, vertical structures, reverse recovery, effects of interface states and temperature on mobility, leakage current, concept of super junction and ultimately the formulation of device physics into compact models.

References

[1] B. Streetman, S. Banerjee, *Solid-State Electronic Devices*, Prentice Hall, 2005.
[2] S. K. Ghandi, *Semiconductor Power Devices: Physics of Operation and Fabrication Technology*, John Wiley & Sons, 1977.
[3] B. J. Baliga, *Modern Power Devices*, Wiley-Interscience, 1987.
[4] B. J. Baliga, *Silicon Carbide Power Devices*, World Scientific Publishing Company, 2006.
[5] B. J. Baliga, *Advanced High Voltage Power Device Concepts*, Springer, 2012.
[6] T. McNutt, A. Hefner, A. Mantooth, D. Berning, R. Singh, "Compact Models for Silicon Carbide Power Devices," *Journal of Solid-State Electronics*, Elsevier, vol. 48, no. 10-11, pp. 1757-1762, Oct.-Nov. 2004.
[7] T. R. McNutt, A. R. Hefner, H. A. Mantooth, J. L. Duliere, D. Berning, R. Singh, "Silicon carbide PiN and merged PiN schottky power diode models implemented in the Saber circuit simulator," *IEEE Trans. on Power Electronics*, vol. 19, no. 3, pp. 573-581, May 2004.
[8] T. R. McNutt, A. R. Hefner, H. A. Mantooth, D. Berning, S.-H. Ryu, "Silicon carbide power MOSFET model and parameter extraction sequence," *IEEE Trans. on Power Electronics*, vol. 22, no. 2, pp. 353-363, Mar. 2007.
[9] M. Saadeh, H. A. Mantooth, J. L. Hudgins, E. Santi, A. Agarwal, S.-H. Ryu, "A Unified Silicon/Silicon Carbide IGBT Model," *IEEE Applied Power Electronics Conference (APEC)*, pp. 1728-1733, Orlando, FL, Feb. 2012.