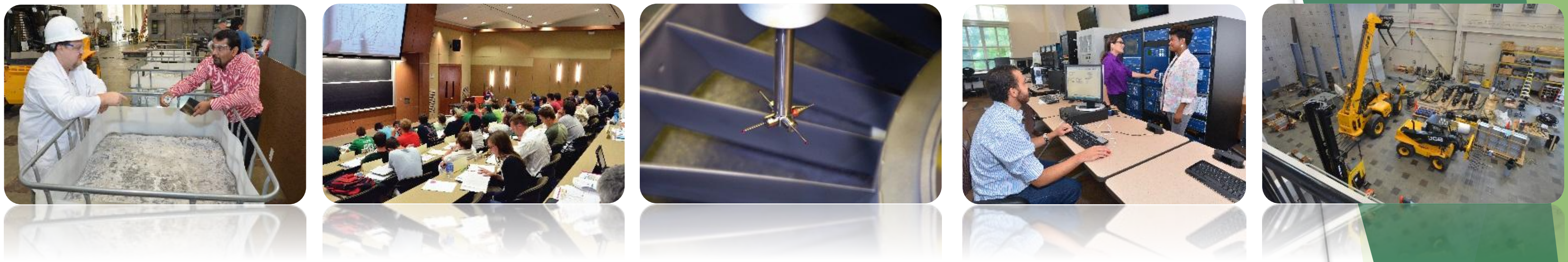

Behavioral Modeling for Stability and Mitigation of Common-Mode Current in Multi-Chip Modules

Presenter: Michael Mazzola

Director, Energy Production and Infrastructure Center (EPIC)

University of North Carolina Charlotte

April 11, 2019

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Energy Production and Infrastructure Center

Overview

- Motivation
- Dynamics and Power Modules – Some Relevant Literature
- Physical vs. Behavioral Modeling – Strengths & Weaknesses
- Commercial Modeling Environments
- DBC Example
- Conclusions & Future Work

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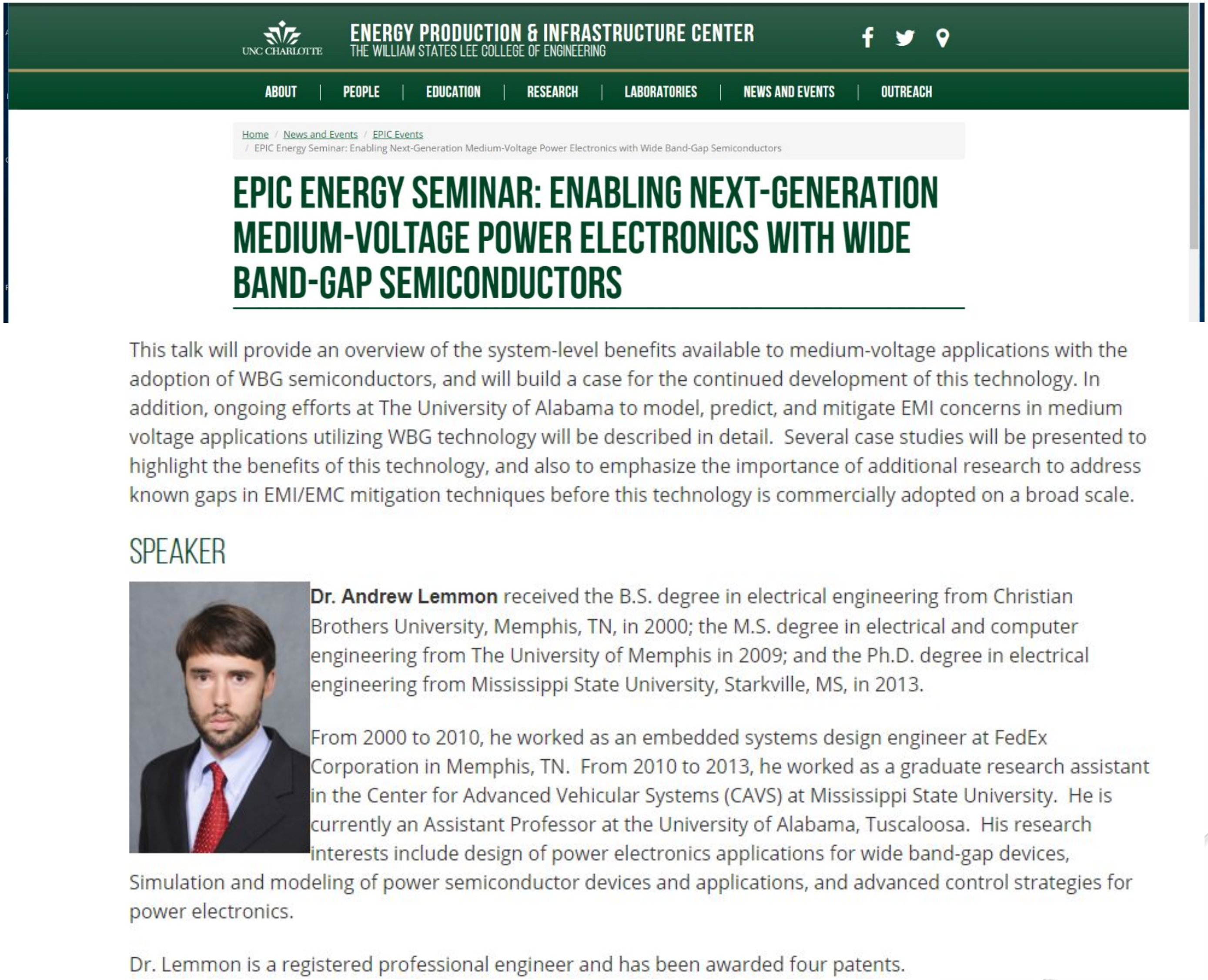
…and also to emphasize the importance of additional research to address known gaps in EMI/EMC mitigation techniques before this technology is commercially adopted on a broad scale.



Home / News and Events / EPIC Events / EPIC Energy Seminar: Enabling Next-Generation Medium-Voltage Power Electronics with Wide Band-Gap Semiconductors

EPIC ENERGY SEMINAR: ENABLING NEXT-GENERATION MEDIUM-VOLTAGE POWER ELECTRONICS WITH WIDE BAND-GAP SEMICONDUCTORS

This talk will provide an overview of the system-level benefits available to medium-voltage applications with the adoption of WBG semiconductors, and will build a case for the continued development of this technology. In addition, ongoing efforts at The University of Alabama to model, predict, and mitigate EMI concerns in medium voltage applications utilizing WBG technology will be described in detail. Several case studies will be presented to highlight the benefits of this technology, and also to emphasize the importance of additional research to address known gaps in EMI/EMC mitigation techniques before this technology is commercially adopted on a broad scale.

SPEAKER

Dr. Andrew Lemmon received the B.S. degree in electrical engineering from Christian Brothers University, Memphis, TN, in 2000; the M.S. degree in electrical and computer engineering from The University of Memphis in 2009; and the Ph.D. degree in electrical engineering from Mississippi State University, Starkville, MS, in 2013.

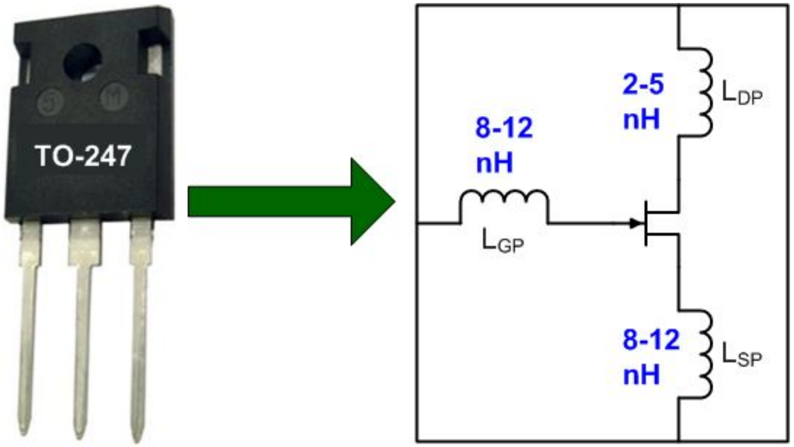
From 2000 to 2010, he worked as an embedded systems design engineer at FedEx Corporation in Memphis, TN. From 2010 to 2013, he worked as a graduate research assistant in the Center for Advanced Vehicular Systems (CAVS) at Mississippi State University. He is currently an Assistant Professor at the University of Alabama, Tuscaloosa. His research interests include design of power electronics applications for wide band-gap devices, Simulation and modeling of power semiconductor devices and applications, and advanced control strategies for power electronics.

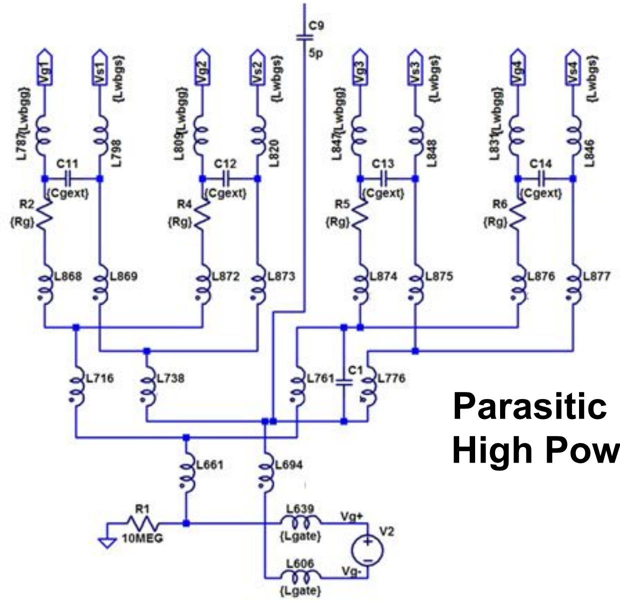
Dr. Lemmon is a registered professional engineer and has been awarded four patents.

Motivation

- Packaging plays a major role in determining performance for WBG systems.
- Wide band-gap devices are fast enough to excite resonances in small parasitic elements.
- WBG Modules: same challenge as discrete packaging, but more complex:
  - Additional die-to-die interconnects.
  - Discrete or distributed representations of parasitics?
  - Some module manufacturers state “low internal inductance” as a scalar figure of merit. But does this make sense?

Typical Parasitic Inductances for TO-247





Parasitic Model For High Power Module

Older literature motivating this work

Power Modules

- J. Gafford, M. Mazzola, G. M. Molen, and C. Parker, “A 1200-V 600-A Silicon-Carbide Half-Bridge Power Module for Drop-In Replacement of an IGBT IPM,” in SAE 2010 SAE World Congress & Exhibition, 2010.
- J. Casady, R. Schrader, D. Sheridan, and V. Bondarenko, “1200 V Enhancement-mode SiC VJFET Power Modules,” in *PCIM Europe*, Nuremberg, Germany, May 2011.
- R. Bayerer and D. Domes, “Parasitic inductance in gate driver circuits”, *PCIM Europe*, Nuremberg, Germany, May 2012
- C. Muller & S. Buschhorn, “Impact of module parasitics on the performance of fast-switching devices,” in *PCIM Europe*, Nuremberg, Germany, May 2014.

Older literature motivating this work (cont.)

Discrete Circuits

- A. Lemmon, M. Mazzola, J. Gafford, and C. Parker, “Stability Considerations for Silicon Carbide Field Effect Transistors,” *IEEE Trans. Power Electronics Letters*, vol. 28, pp. 4453-4459, 2013.
- A. Lemmon, M. Mazzola, J. Gafford, and C. Parker, “Instability in Half-Bridge Circuits Switched with Wide Band-Gap Transistors,” *IEEE Trans. Power Electronics* (special issue), vol. 29, no. 5, pp. 2380-2392, 2014.
- M. Shahverdi, M. Mazzola, R. Schrader, A. Lemmon, C. Parker, and J. Gafford, “Active Gate Drive Solutions for Improving SiC JFET Switching Dynamics,” *Proc. 2013 IEEE APEC*, Long Beach, CA, 17-21 March 2013, pp. 2739-2743.
- J. Gafford, M. Mazzola, A. Lemmon, C. Parker, “Stable High dV/dt Switching of SiC JFETs Using Simple Drive Methods,” *Proc. 2013 IEEE APEC.*, Long Beach, CA, 17-21 March 2013, pp. 2450-2452.

Recent literature

Common current modeling and EMI mitigation

- M. Rahmani, M. Mazzola, and S. Yarahmadian, “Wavelet-Based Time-Domain Solutions for Common-Mode Currents on Open-Form Conductors Modeled With Band-Limited Scattering Parameters,” *IEEE Trans. Components, Packaging, and Manufacturing Technology*, vol. 3, pp. 549-556, 2019.
- A. Lemmon, R. Cuzner, J. Gafford, R. Hosseini, A. Brovont, and M. Mazzola, “Methodology for Characterization of Common-Mode Conducted Electromagnetic Emissions in Wide-Bandgap Converters for Ungrounded Shipboard Applications,” *IEEE J. Emerging and Selected Topics in Power Electronics*, vol. 6, pp. 300-314, 2018.
- A. Brovont and A. Lemmon, “Common-Mode/Differential-Mode Interactions in Asymmetric Converter Structures,” *IEEE Electric Ship Tech. Symp.*, DOI: 10.1109/ESTS.2017.8069264,14-17 Aug. 2017.

J. Gafford, M. Mazzola, G. M. Molen, and C. Parker, “A 1200-V 600-A Silicon-Carbide Half-Bridge Power Module for Drop-In Replacement of an IGBT IPM,” in SAE 2010 SAE World Congress & Exhibition, 2010.

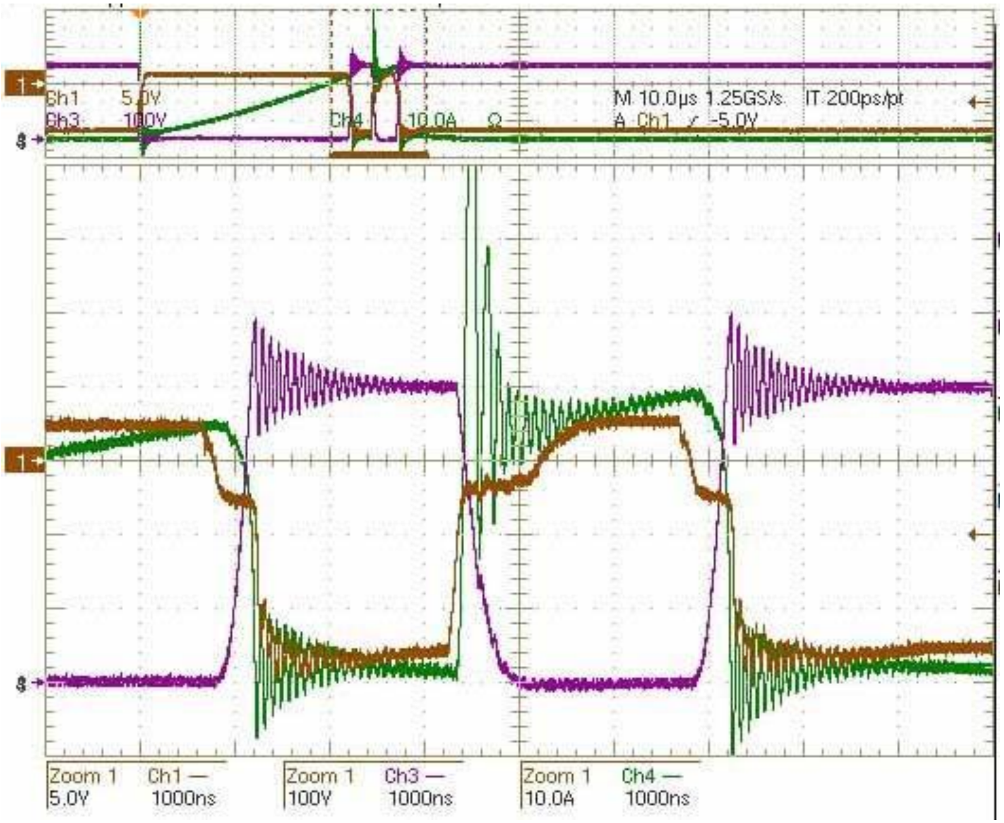


Figure 4. Switching result from Clamped Inductive Load test. The brown trace (Ch1) is gate-source voltage (5 V/div). The purple trace (Ch3) is drain-source voltage (100 V/div). The green trace (Ch4) is drain current (10 A/div).

J. Casady, R. Schrader, D. Sheridan, and V. Bondarenko, “1200 V Enhancement-mode SiC VJFET Power Modules,” in *PCIM Europe*, Nuremberg, Germany, May 2011.

- Normally-off SiC VJFET power module
  - 1200 V, 100 A rated
  - Each switch is 4 x 50mΩ die in parallel
  - Integral SiC Freewheeling diodes
  - Kelvin source for gate driver
  - Internal DC bus and gate-source snubbers for improved performance at high dV/dt
  - AlN DBC ceramic
  - Case approximately 4 cm x 5 cm

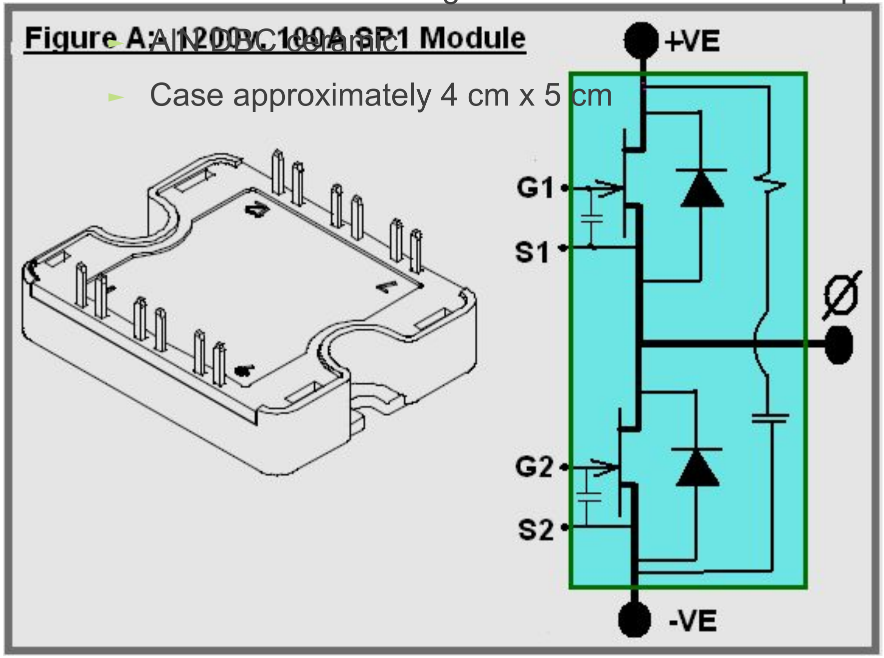
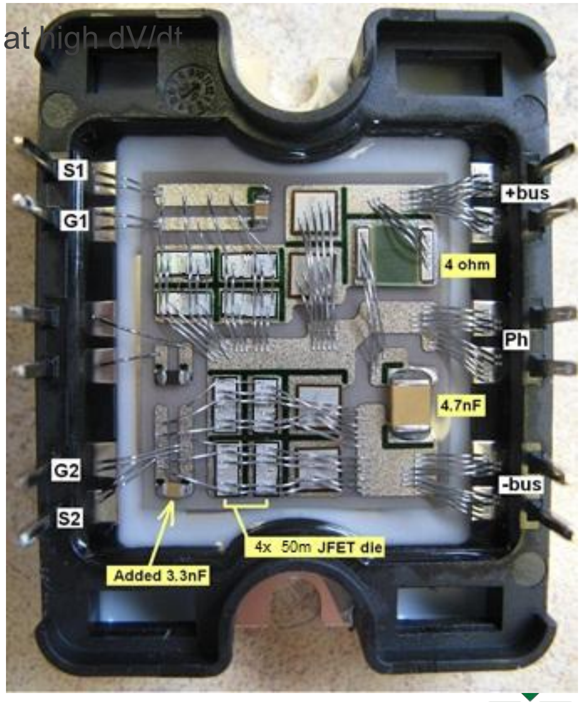


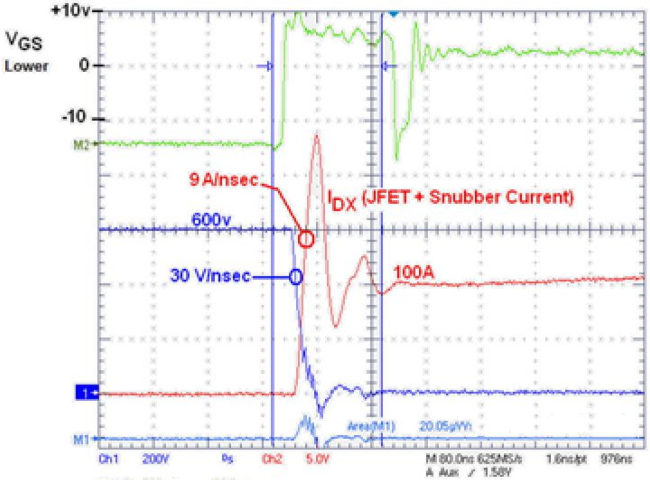
Figure A: 1200V 100A SP1 Module



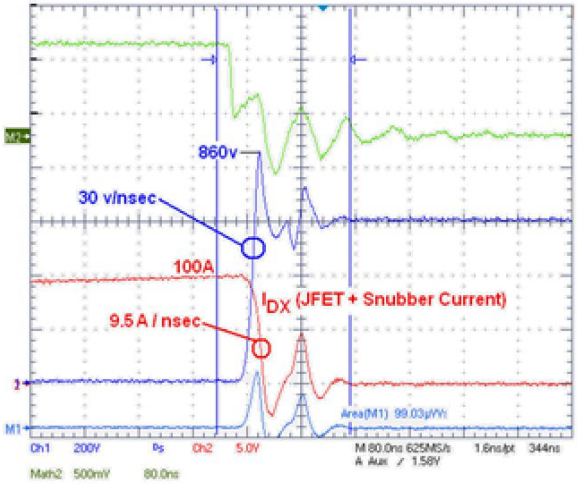
J. Casady, R. Schrader, D. Sheridan, and V. Bondarenko, “1200 V Enhancement-mode SiC VJFET Power Modules,” in *PCIM Europe*, Nuremberg, Germany, May 2011.

Initial Switching Results

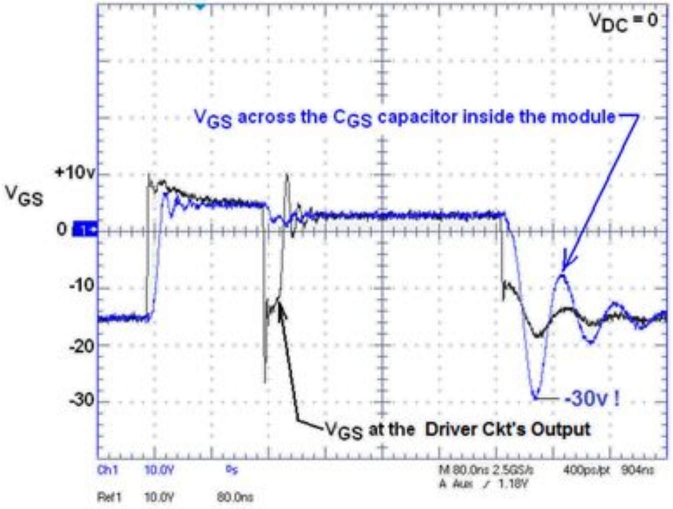
- Undesirable oscillations at turn-on
- Oscillation at turn-off drives device into conduction for a short period before remaining off
- Gate voltage measured internal to the module shows oscillation at the die level



Turn-on



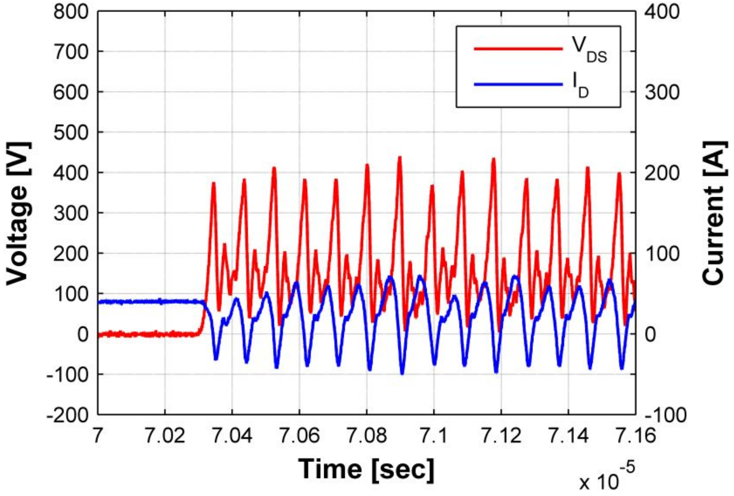
Turn-off

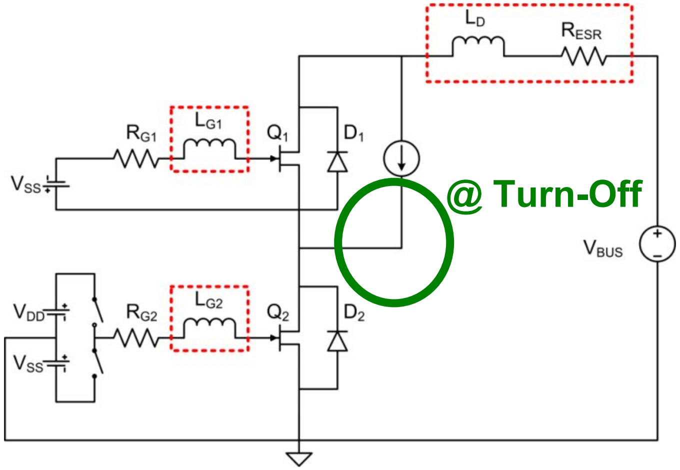


A. Lemmon, M. Mazzola, J. Gafford, and C. Parker, “Stability Considerations for Silicon Carbide Field Effect Transistors,” *IEEE Trans. Power Electronics Letters*, vol. 28, pp. 4453-4459, 2013.

- The presence of L_G makes this circuit susceptible to **self-sustained oscillation**
- This occurs at turn-off of the active switch, after the Miller period.
- This phenomenon is **<u>NOT</u>**:
  - The natural response of the power loop
  - Shoot-through due to displacement current
  - Spurious re-trigging of the gate drive PWM input

Self-Sustained Oscillation



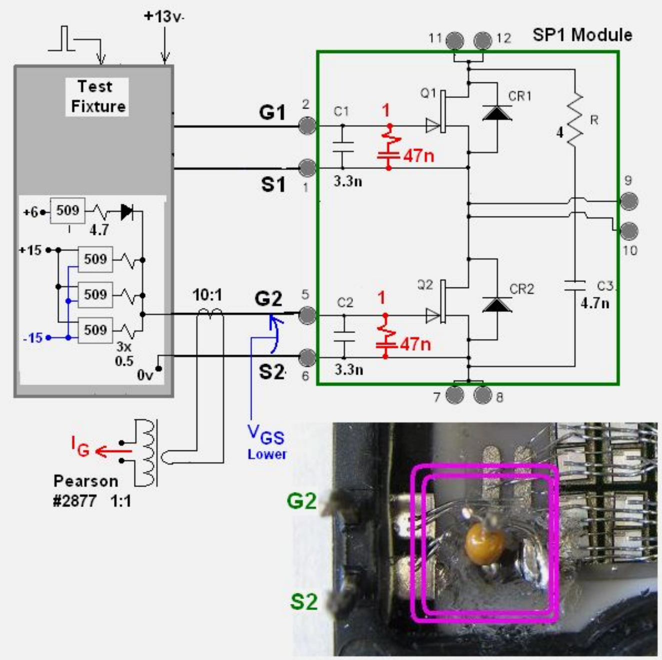


@ Turn-Off

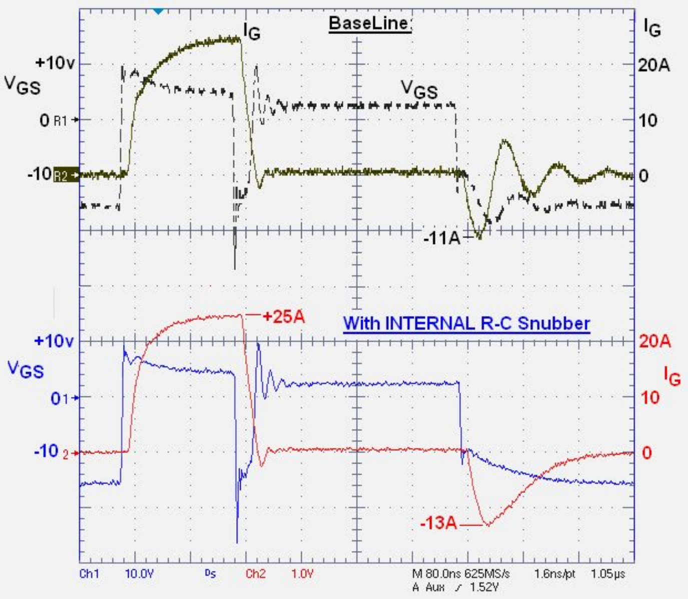
J. Casady, R. Schrader, D. Sheridan, and V. Bondarenko, “1200 V Enhancement-mode SiC VJFET Power Modules,” in *PCIM Europe*, Nuremberg, Germany, May 2011.

- Simulation suggested an R-C snubber in parallel with the gate-source would aid in damping oscillations.
- Increasing C_{GS} only reduced the frequency of oscillation.
- The required R and C were added to the module DBC.
- Gate voltage ringing inside the module was eliminated.

Addition of R-C Gate Snubber Internal to the Module



Measured Gate Waveforms (Zero DC Bus).



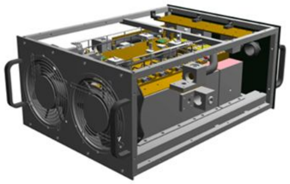
Need for an Integration Tool

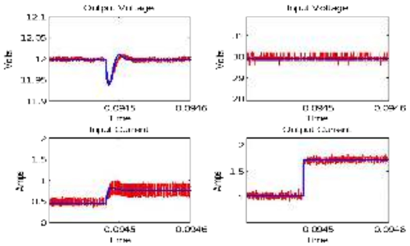
Physical Descriptions

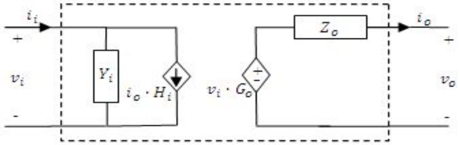
Validation

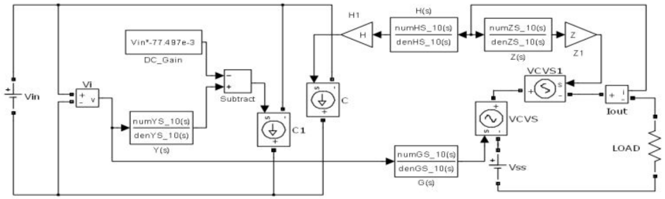
Abstract Descriptions

Power Conversion Modules



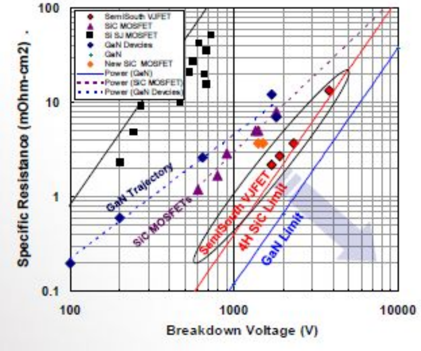


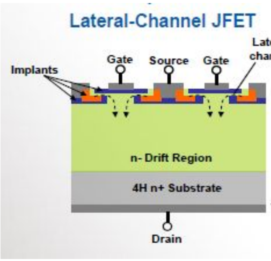


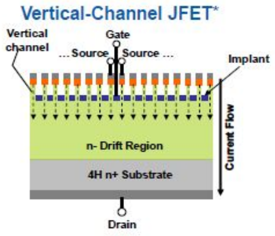


The hole in the middle: Integrating die into the system

Power Semiconductor Devices







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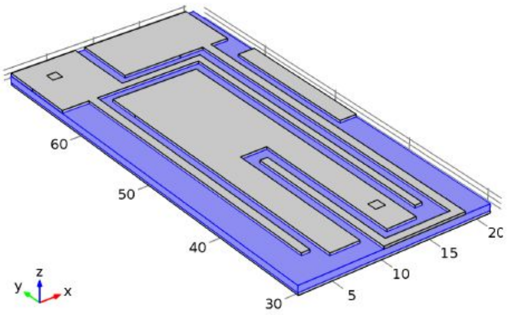
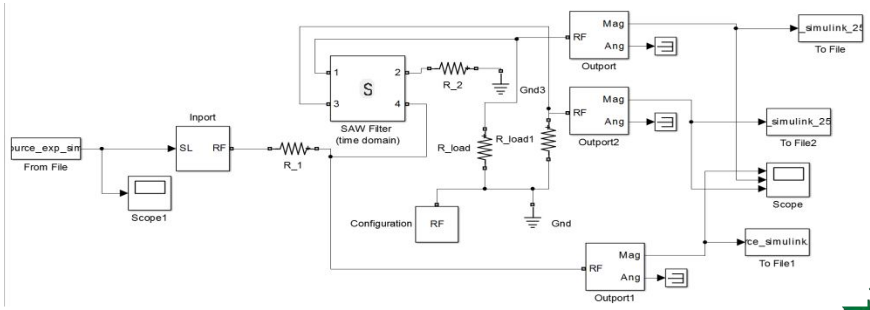
Physical vs. Behavioral Modeling of Power Modules

- Physical Modeling
- Strengths
  - Robust and Reliable
  - Complex Geometry by method of finite-elements
  - Multi-physics
- Weakness
  - Computationally expensive
  - Often incompatible with other behavioral modeling

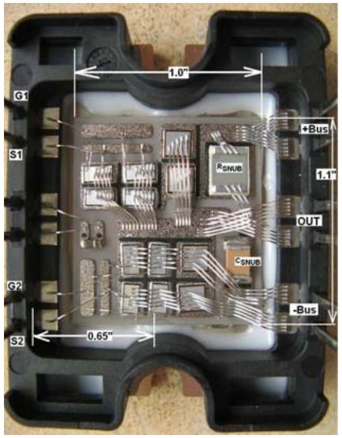
- Behavioral Modeling
- Strengths
  - Computationally inexpensive
  - Compatible with circuit solvers
  - Suitable for optimization
- Weakness
  - Careful validation and documentation required

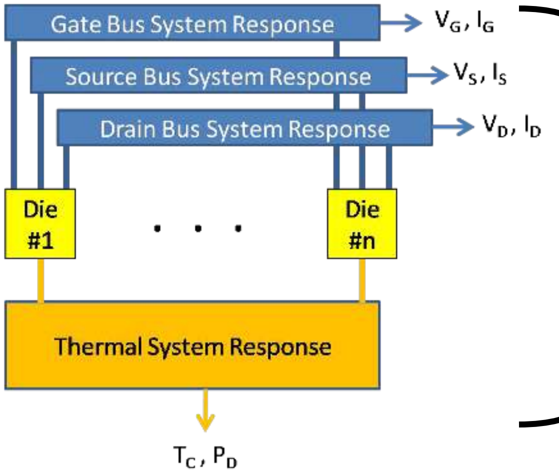


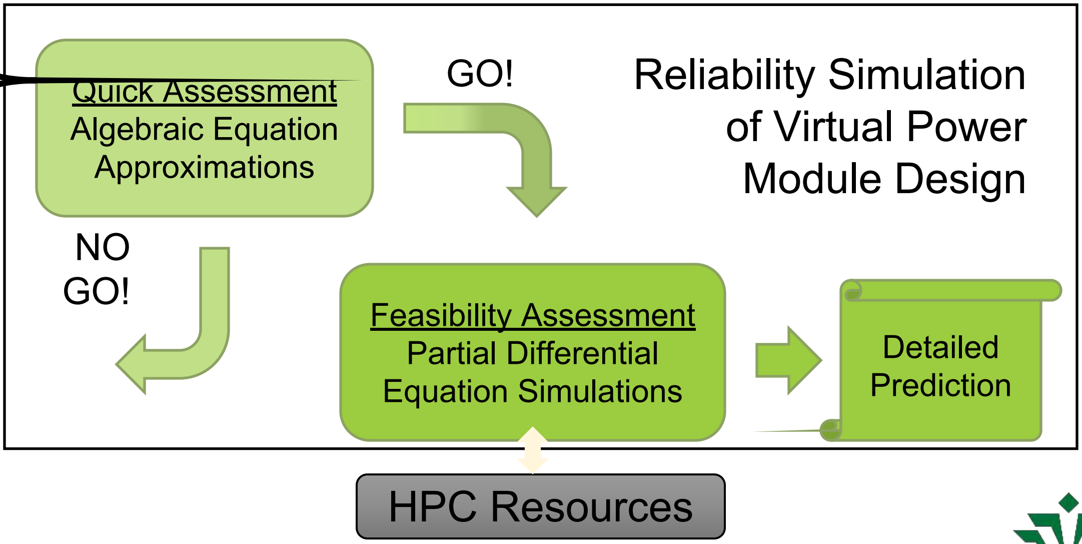


Multi-Scale & Multi-Physics Analytical Tools for Design of Virtual Power Modules

- Develop scalable power module models
  - Arbitrary sized modules
  - Power module scaling procedure is analogous to physical construction
    - Physics-Based in Development / Behavioral in Simulation
    - Three sub-component meta-models (die, package interconnects, package thermal)
    - <u>Non-linearity principally limited to sub-scale models of semiconductor devices</u>
    - Libraries of individual models used to create a virtual package







<u>Quick Assessment</u>
Algebraic Equation Approximations

GO!

Reliability Simulation of Virtual Power Module Design

NO GO!

<u>Feasibility Assessment</u>
Partial Differential Equation Simulations

Detailed Prediction

HPC Resources

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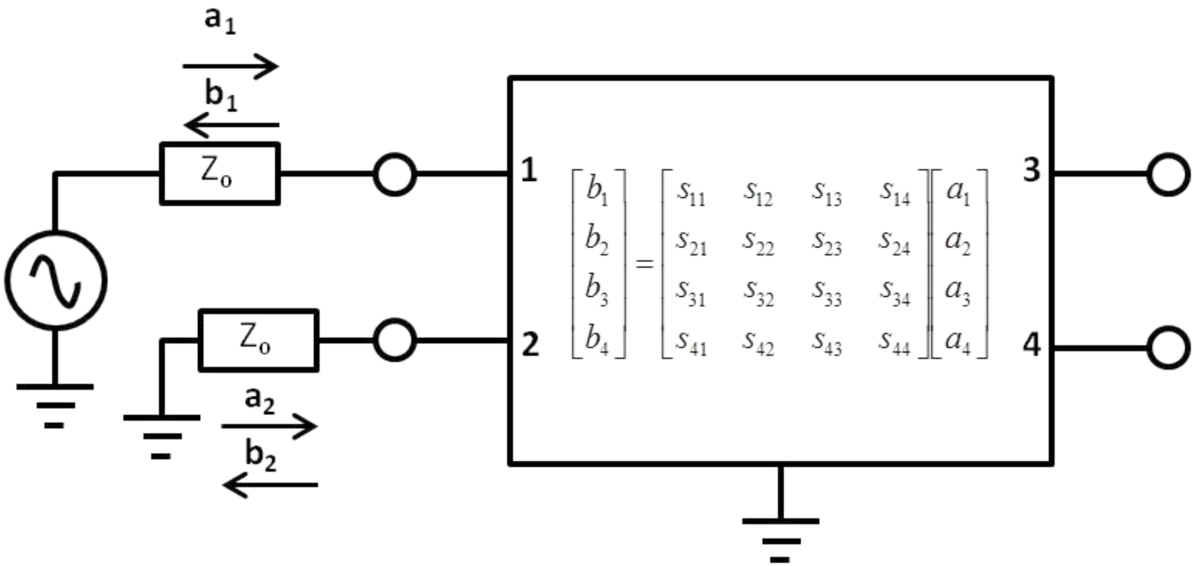
Modeling Tools Evaluated

Tool	Multi-physics	S-parameter Extraction	Circuit Analysis
COMSOL	●	●	
EMPro		●	
ADS		●	●
Simulink			●

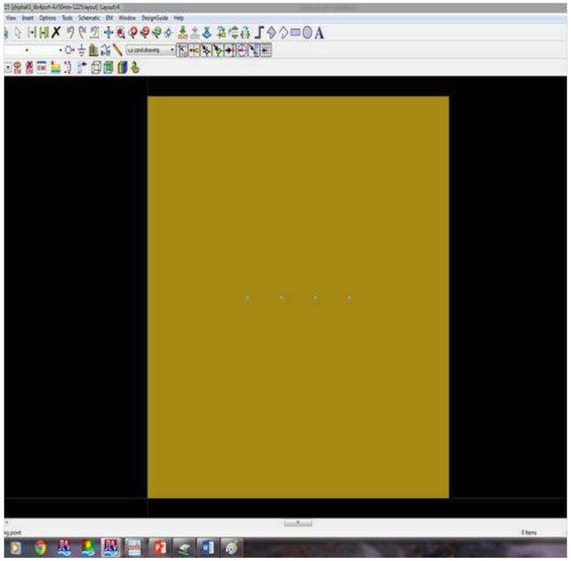
S-parameter Behavioral Modeling

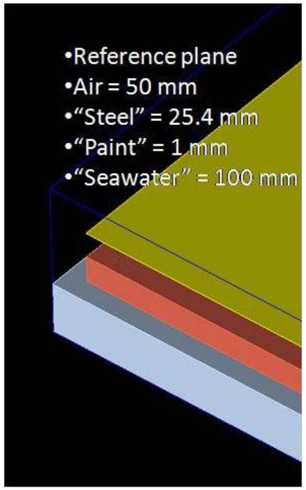


$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} & s_{13} & s_{14} \\ s_{21} & s_{22} & s_{23} & s_{24} \\ s_{31} & s_{32} & s_{33} & s_{34} \\ s_{41} & s_{42} & s_{43} & s_{44} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix}$$

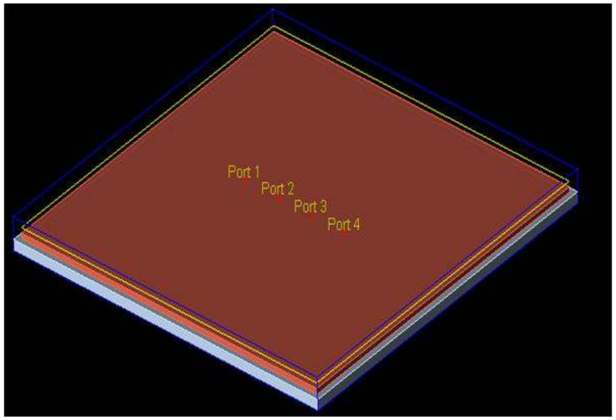
- Linear
- Broadband
- Scalable
- Circuit based solutions

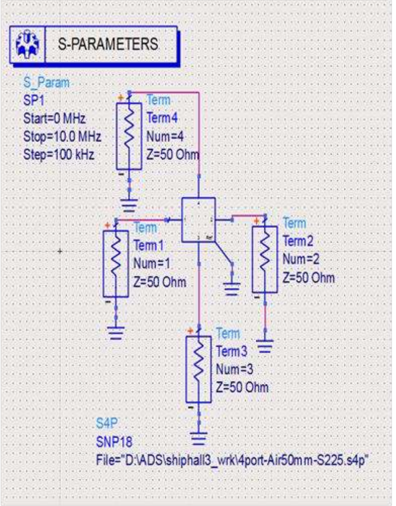
Extracting S-parameter models





- Reference plane
- Air = 50 mm
- "Steel" = 25.4 mm
- "Paint" = 1 mm
- "Seawater" = 100 mm





S-PARAMETERS

S_Param
SP1
Start=0 MHz
Stop=10.0 MHz
Step=100 kHz

Term
Term4
Num=4
Z=50 Ohm

Term
Term1
Num=1
Z=50 Ohm

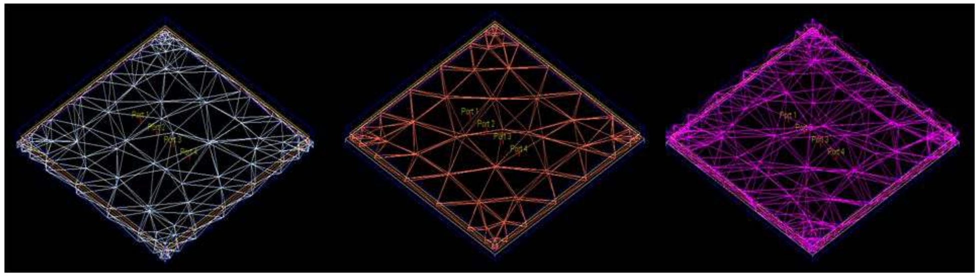
Term
Term2
Num=2
Z=50 Ohm

Term
Term3
Num=3
Z=50 Ohm

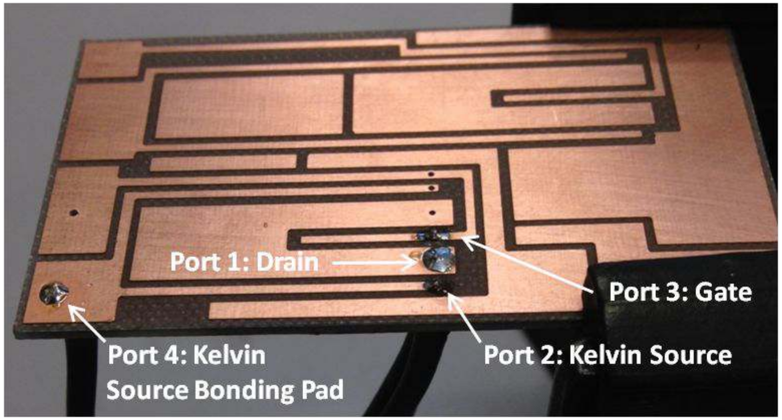
S4P
SNP18
File="D:\ADS\shiphall3_wrk\4port-Air50mm-S225.s4p"

Physics based calculation of S-parameter model of a four-port square block in Agilent ADS

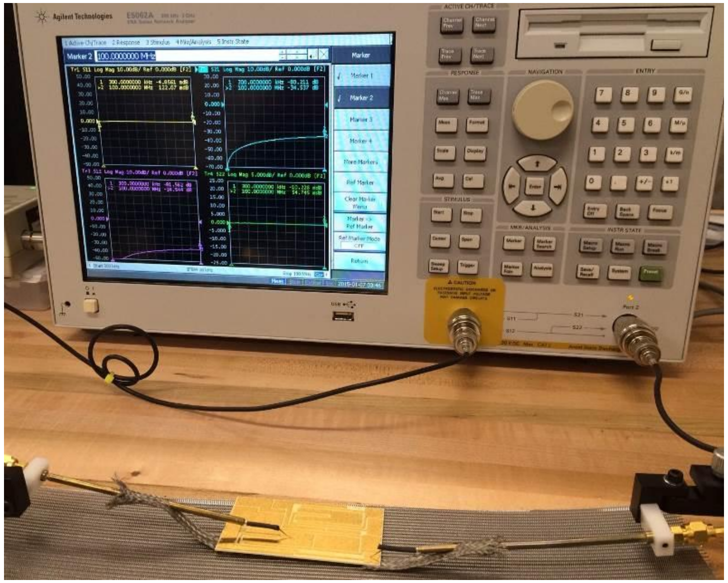
- Finite element analysis with auto-generated mesh
- Frequency range is zero to 10 MHz



DBC Example



DBC made from a FR4 milled printed circuit board. Ports are defined with RG-174 coaxial cable probes with the shields soldered to the copper plane on the bottom of the board. Tektronix Arbitrary Waveform Generator and Digital Scope for time-domain measurements.



Agilent Vector Network Analyzer for frequency-domain (S-parameter) measurements.

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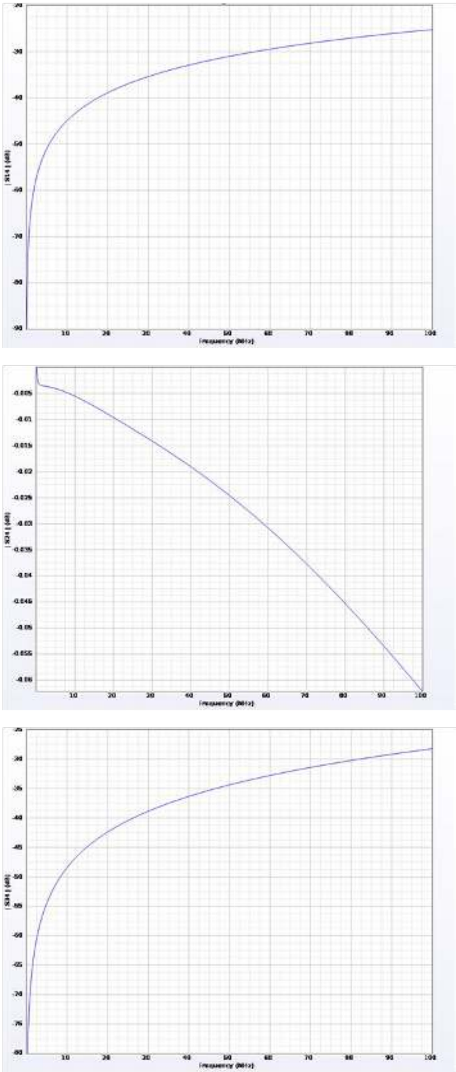
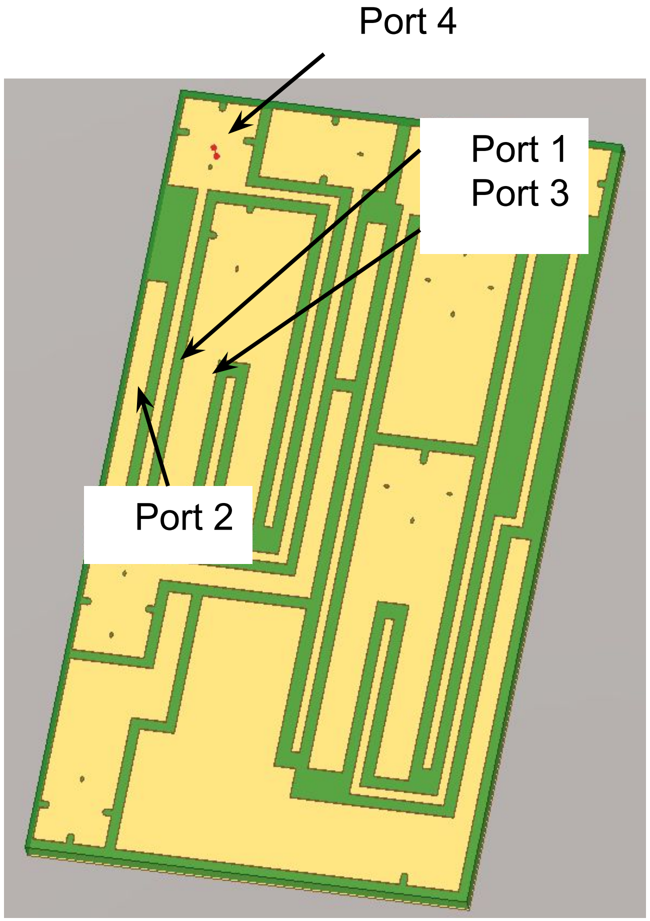
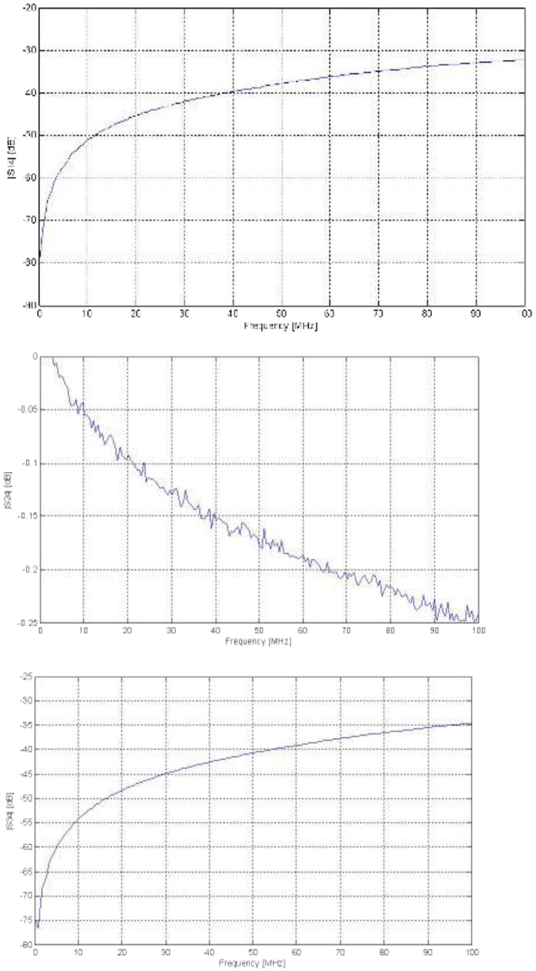
Calculated vs. Measured S-Parameters



Calculated magnitudes of the transmission between port 4 and the other three ports. (a) $|S_{14}|$; (b) $|S_{24}|$; (c) $|S_{34}|$.





Measured magnitudes of the transmission between port 4 and the other three ports. (a) $|S_{14}|$; (b) $|S_{24}|$; (c) $|S_{34}|$.

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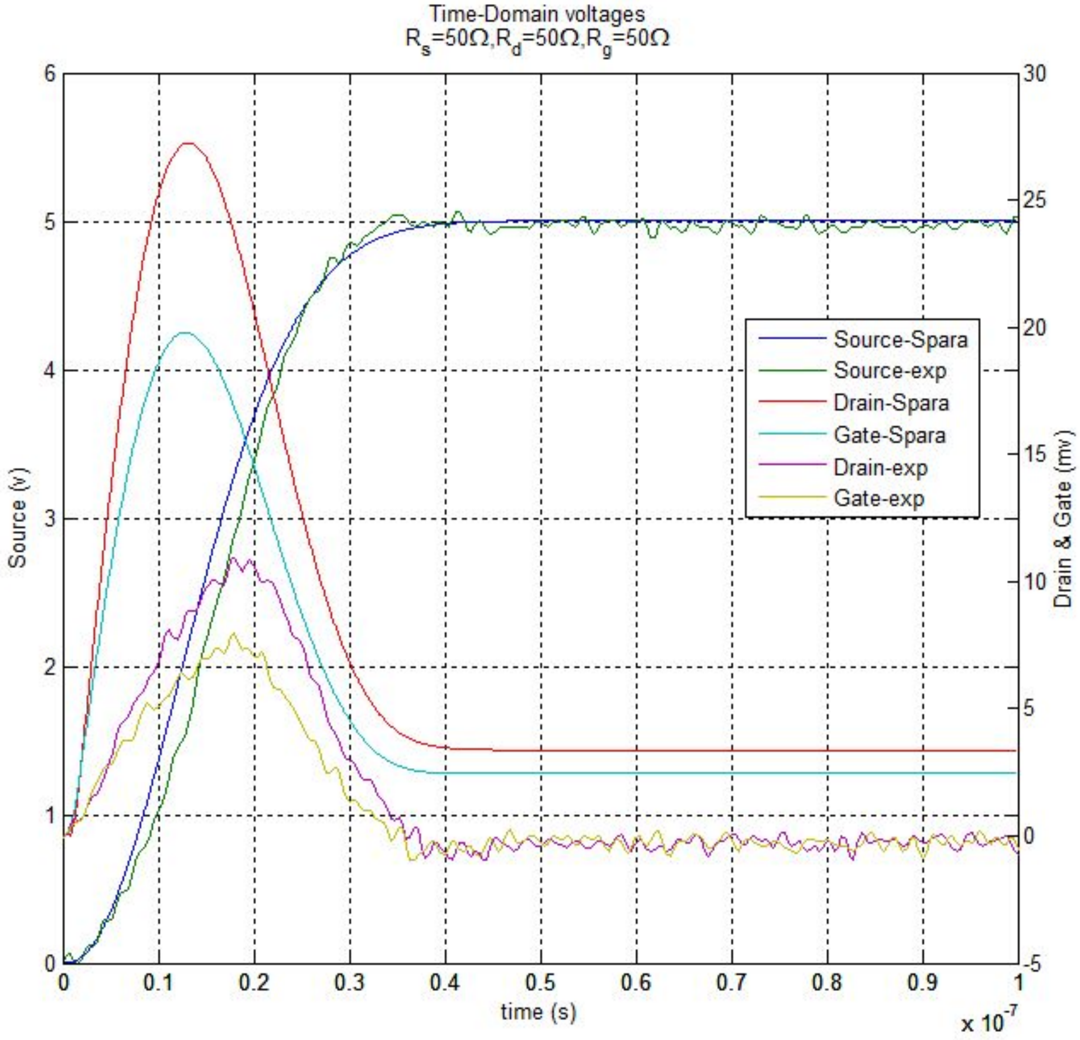
Calculated vs. Measured in Time Domain



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Conclusions and Future Work

- Behavioral modeling of power packaging traceable to physics can be done with commercial tools.
- Applications include rapid and computationally low cost design for stability and common-mode current mitigation.
- S-parameter behavioral modeling especially attractive for “near-RF” performance of wide bandgap power semiconductors.
- Work flow reduces judgment in extracting parameters to a minimum and can be automated.
- Future work needed to integrate with industry standard tools used by the power packaging industry.
- Novel applications in 3D printed die/gate-drive/application integration.