HESSE MECHATRONICS

PREES Laboratory
NC STATE UNIVERSITY
PACKAGING RESEARCH IN ELECTRONIC ENERGY SYSTEMS

Flexible Welded Interconnects for Crosstalk Reduction in WBG Power Modules

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CSME - April 11-13, 2017

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Packaging Research in Electronic Energy Systems (PREES)

Circuit Design Beyond the Schematic

A one of a kind power electronics packaging and design lab. Located at North Carolina State University, and a subset of the ***FREEDM*** Systems Center and PowerAmerica Institute. ***PREES*** focuses on power electronics research.

Mission Statement: *Combining Industry and research interests to confront the world's energy problems through R&D of power electronics. Focusing in electro-physical design, device packaging, and use of 3D additive manufacturing….And the education of the next generation high-tech workforce.*

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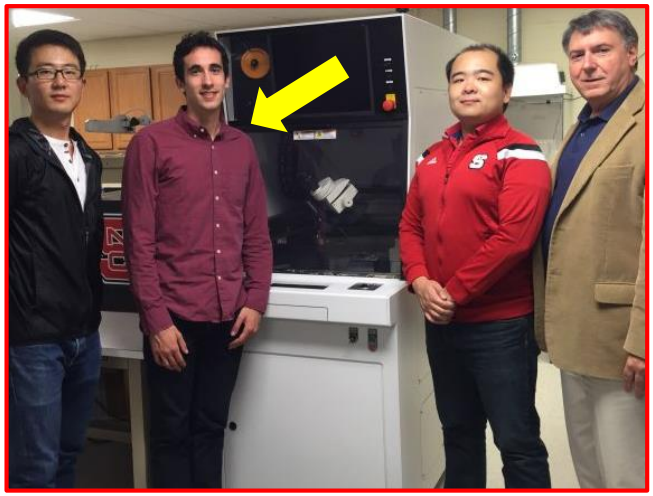
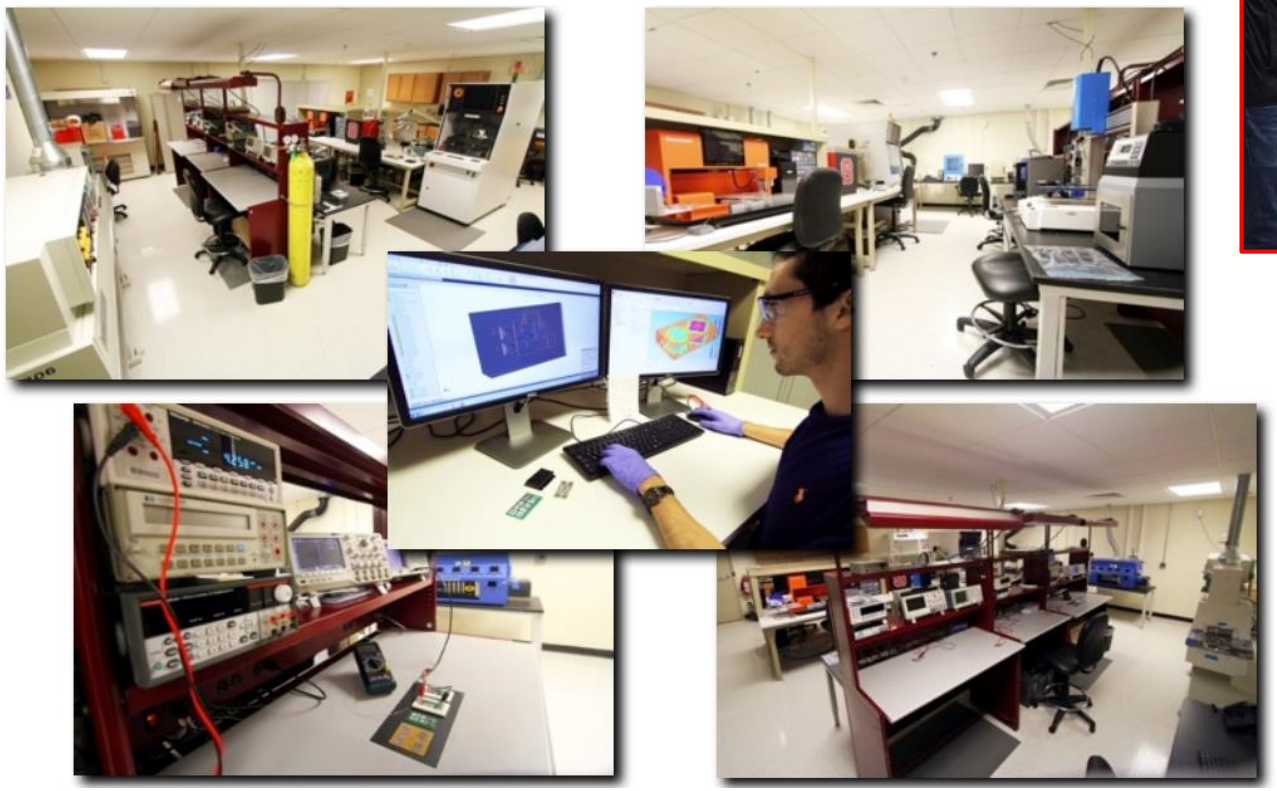
PREES Lab at North Carolina State University

Concurrently design multi-energy circuits (electrical, mechanical, thermal, etc.) that cross cuts all levels of packaging





Adam Morgan – Power module design focused in the VHF range for green energy technology

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Introduction

Wide-bandgap (WBG) power semiconductor devices are driving new packaging designs! → high frequency, temperature, voltage operation

"Flexible welded interconnects" (wire/ribbon bonds) have many advantages, but also negatively contribute to:

- Power losses within the power module, and ultimately affect overall efficiency, at higher frequencies
- EMI problems, such as crosstalk and common/differential mode noise

Electro-physical topologies of power substrates and Al or Au wire/ribbon bonds are characterized using high frequency circuit analysis techniques

- Segmented vs Lumped Parameter Models
- Odd and Even Mode coupling impact on total interconnect impedance
- Near and Far End crosstalk dependency

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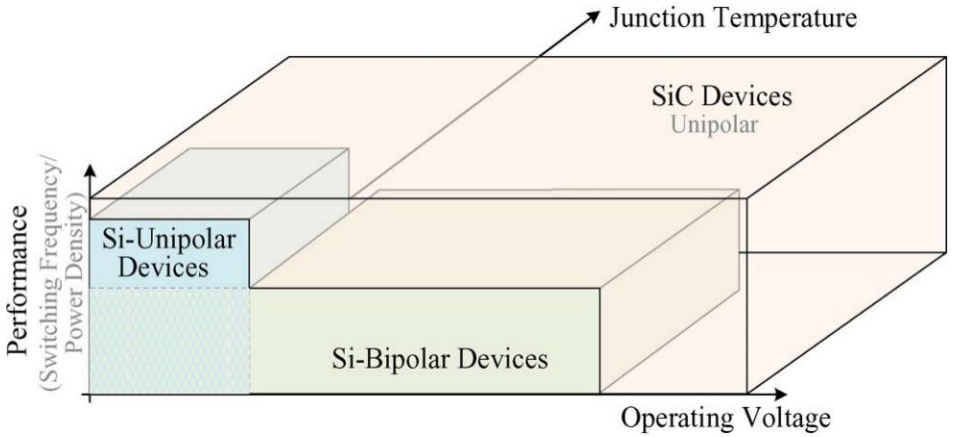
WBG versus Silicon

- WBG power semiconductor devices offer many performance improvements over conventional Si technology, especially at larger operating voltages

	Silicon	4H-SiC
Energy Bandgap (eV)	1.11	3.26
1.5kV diode switch-off reverse recovery time (ns) *	670	100
Thermal Conductivity (W/cm-K)	1.5	3.7



F. Nallet, D. Planson, K. Isoird, M. L. Locatelli and J. P. Chante. Comparison of static, switching and thermal behavior between a 1500 V silicon and silicon carbide bipolar diodes. Presented at Semiconductor Conference, 1999. CAS '99 Proceedings. 1999 International. 1999, . DOI: 10.1109/SMICND.1999.810461.

J. Biela, M. Schweizer, S. Waffler and J. W. Kolar. SiC versus Si—Evaluation of potentials for performance improvement of inverter and DC–DC converter systems by SiC power semiconductors. *Industrial Electronics, IEEE Transactions on 58(7),* pp. 2872-2882. 2011. . DOI: 10.1109/TIE.2010.2072896.

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WBG for Higher Breakdown Voltage

- The appropriate technology needs to be selected for the desired application, and WBG dominates at higher operating voltages

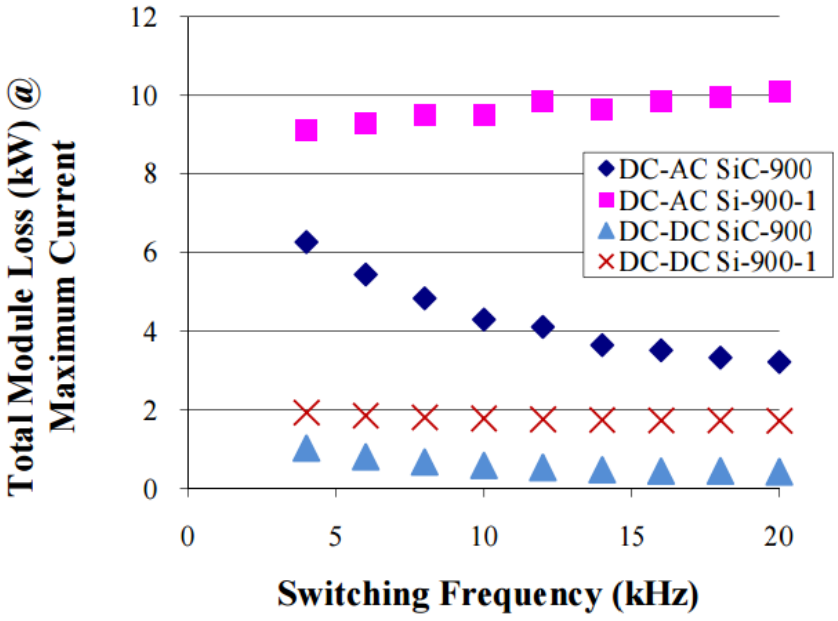
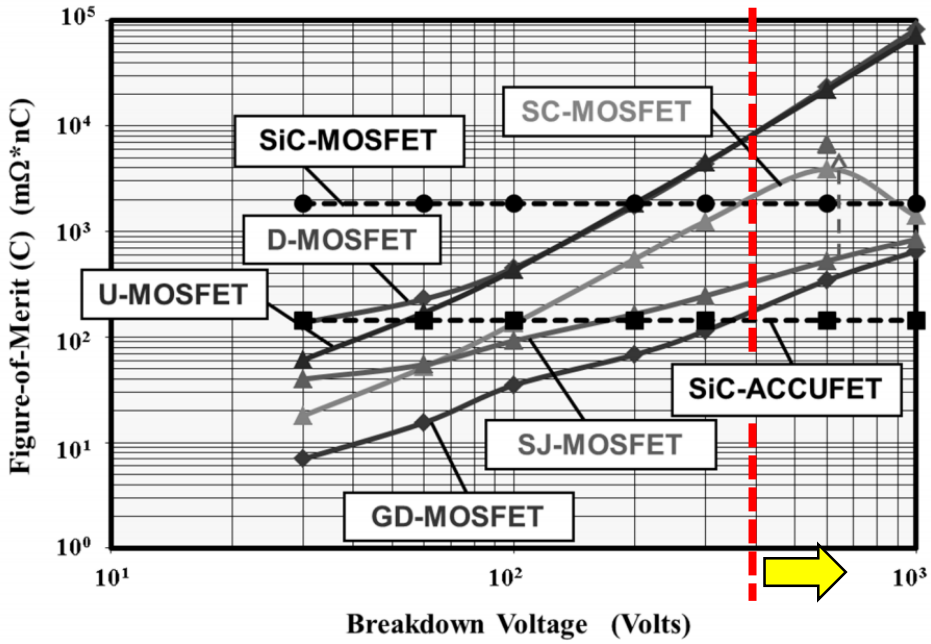


Figure 6. Total Module Loss for Si-900-1 and SiC-900.

R. A. Wood and T. E. Salem. Application study of the benefits for using silicon-carbide versus silicon in power modules. Presented at Applied Power Electronics Conference and Exposition (APEC), 2012 Twenty-Seventh Annual IEEE. 2012, . DOI: 10.1109/APEC.2012.6166173.

$$FOM(C) = R_{on,sp}Q_{GD,sp}$$



→Inductive Load Turn-off:
P_D = 100W/cm^2, I_{ON} = 10A, V_{DC} = 400V

J. Baliga, "Synopsis," in *Advanced Power MOSFET Concepts,* 1st ed. New York, NY, Springer, 2010 , ch. 10, sec. 10.3 Device Comparison, pp. 549-552.

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Decreasing Power Loss Through WBG Devices

- Power MOSFET Relation for Min. Power Dissipation FOM(B) = $R_{on,sp}$ * $C_{in,sp}$

$$P = K_1 F_{SW} C_{SW} V_{DC}^2$$

- Greater V_{in} → greater voltage overshoot/stress across the power MOSFET, therefore need high V_{BR} rating of the device, which negatively impacts FOM(B) by a factor of 4/3

- WBG devices have better FOM(B) and enable VHF converter topologies into the medium voltage range

$$R_{SW} C_{SW} = \frac{\epsilon_{Si}}{q\mu_n} \frac{V_{BR}^{\frac{4}{3}}}{2.0 \times 10^{18}}$$

V_{BR} = 1.2 kV	Si	4H-SiC	GaN
N_D [cm^{-3}]	1.56e14	1.55e16	3.12e16
μ_n [cm^2/V-s]	1357	951	967
ε_r [F/m]	11.68	9.66	10.4
$R_{SW}C_{SW}$ [s]	3.04e-9	3.62e-11	1.91e-11

Very High Frequency (30MHz–300MHz) switching is possible in resonant power converters

- Minimize heavy switching losses associated with PWM-based converters that have rectangular voltage and current waveforms
- Higher power densities achieved, yet new high frequency problems arise!

J. S. Glaser, J. Nasadoski and R. Heinrich, "A 900W, 300V to 50V Dc-dc Power Converter with a 30MHz Switching Frequency," *Applied Power Electronics Conference and Exposition, 2009. APEC 2009. Twenty-Fourth Annual IEEE*, Washington, DC, 2009, pp. 1121-1128. doi: 10.1109/APEC.2009.4802804

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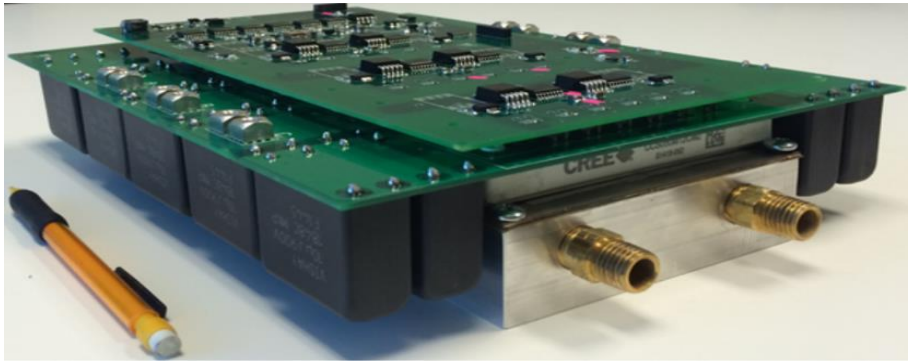
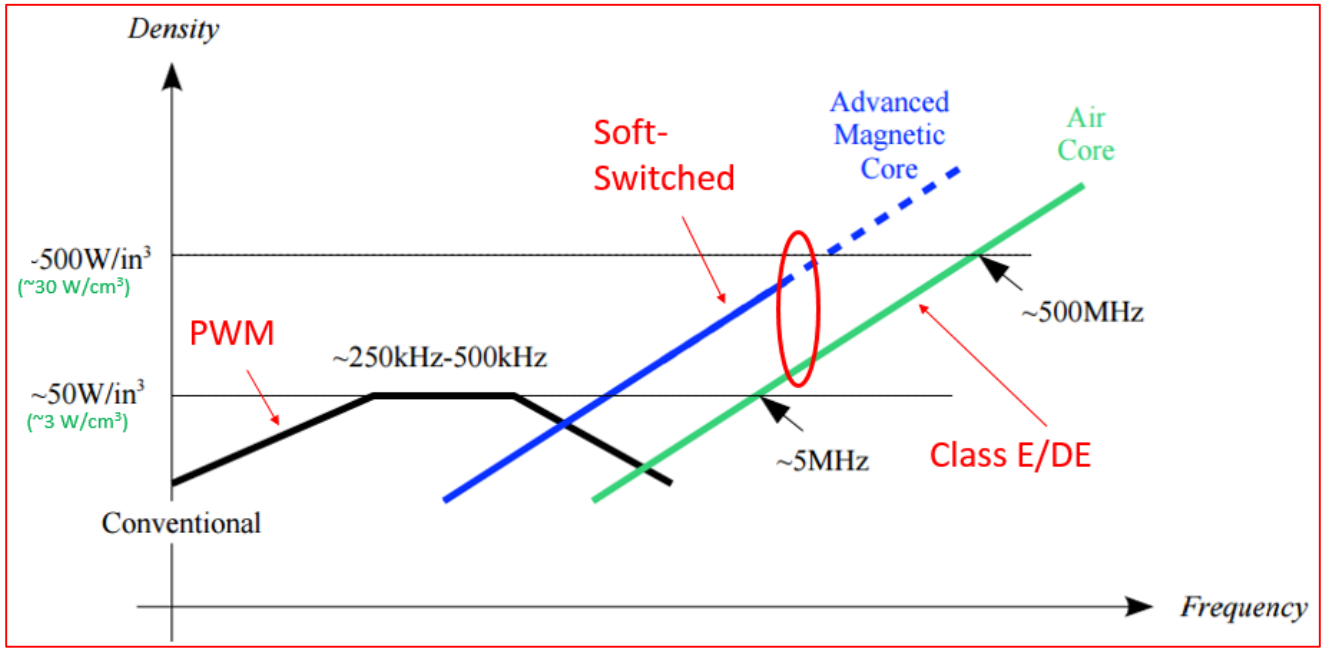
Converter Power Density Estimates vs. f_{sw}

PowerAmerica SiC Traction Inverter

- Prated = 55kW
- Volume = 4500cm^3
- Power density = 12.1kW/L
- F_{sw} = 35kHz – 70kHz





FINSix Power Adapter

- Prated = 65W
- Volume = 54.5cm^3
- Power density = 1.2kW/L
- F_{sw} = 30MHz – 300MHz

John S. Glaser; Jeffrey Nasadoski; Richard Heinrich, *A 900W, 300V to 50V Dc-dc Power Converter with a 30MHz Switching Frequency,* Applied Power Electronics Conference and Exposition, 2009. Twenty-Fourth Annual IEEEYear: 2009. Pages: 1121 - 1128, DOI: 10.1109/APEC.2009.4802804

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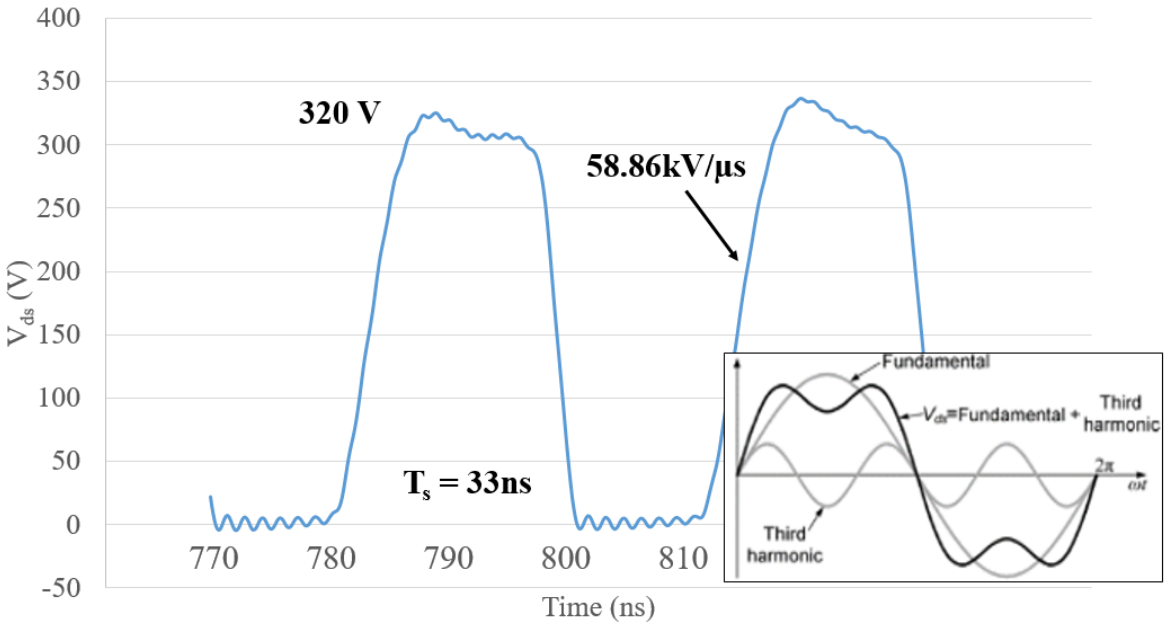
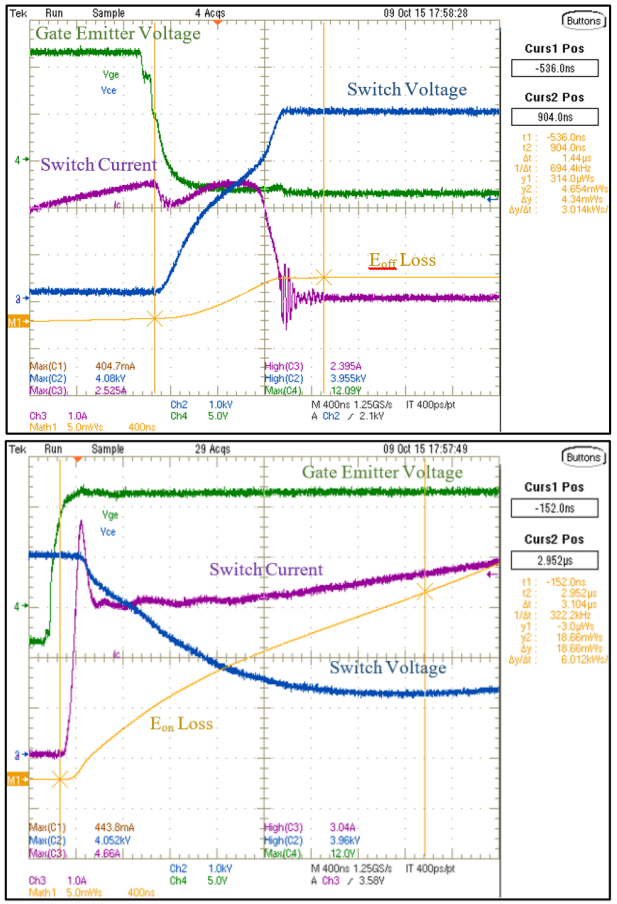
Voltage & Current Waveform Edge Rates

Wide-bandgap (WBG) power semiconductor devices are capable of producing must faster edge rates than conventional Silicon power semiconductor devices

- SiC MOSFETs & GaN HEMTs → 50kV/µs





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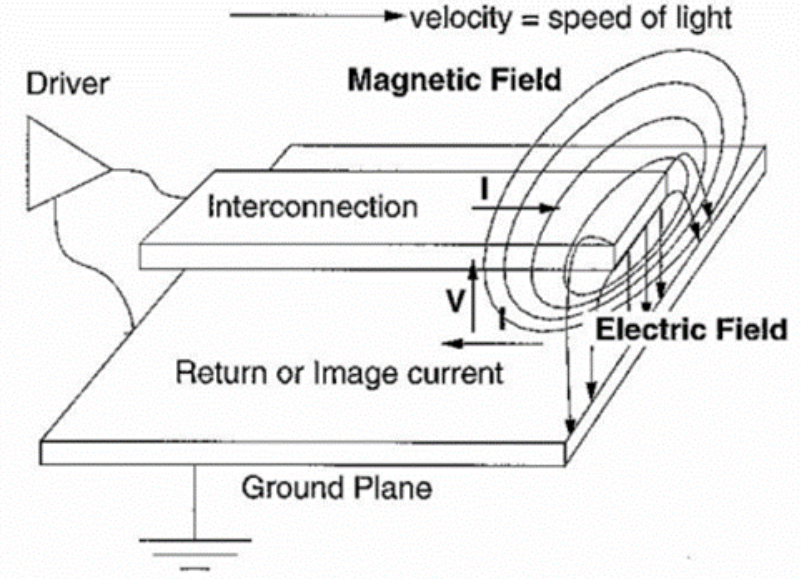
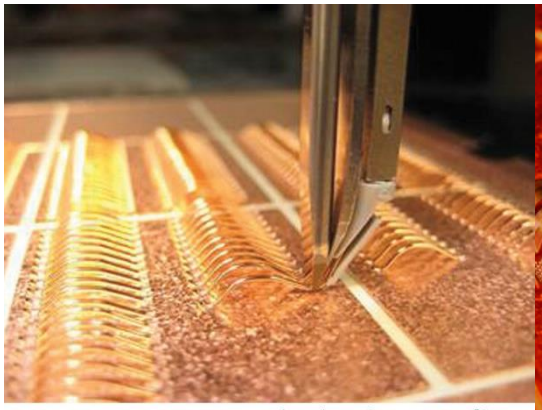
High Density Flexible Welded Interconnects

- Wire and ribbon bonds can have undesirable parasitic effects that impact performance, especially at higher operating frequencies, when carrying waveforms with fast rise/fall times
- Treat interconnects as transmission lines within the module
  - All that is required for the creation of a transmission line are two conductors:
    - Signal Line = wire or ribbon bond
    - Return Path = adjacent interconnects, conductor pads, substrate metallizations





Heavy Copper (Cu) Wire Bonding
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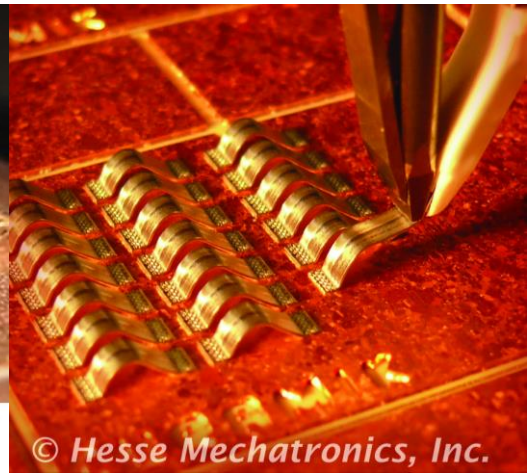

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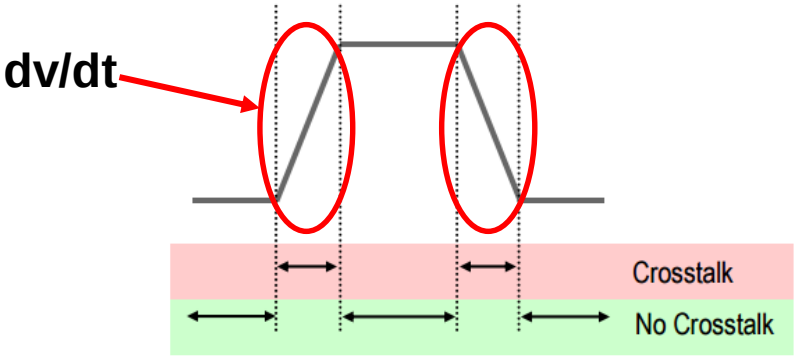
Focus on the Dynamics

As F_{sw} increases, wavelengths decrease → electro-physical topology matters!

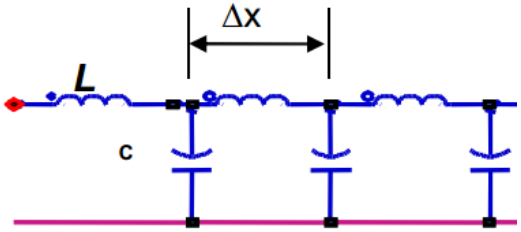
Why are edge rates the problem? (Lec 5, slide 5)

- Transmission line behavior
- Power/ground plane bounce
- Cross-talk
- EMI

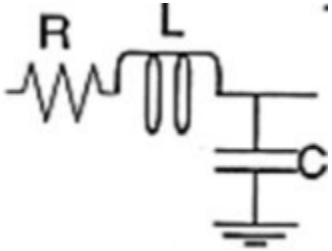


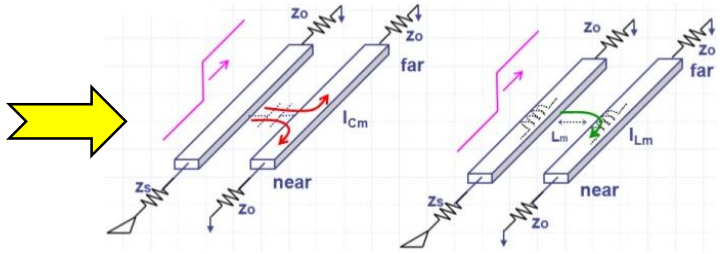
If circuit discontinuities:

- > (λ/10), need to analyze circuits with a segmented model
- < (λ/10), need to analyze circuits with a lumped parameter model



or





Mutual inductance/capacitance between "flexible welded interconnects" should be considered under high power density and high frequency switching

→Better understanding/modeling enables better prediction of **crosstalk** generated!

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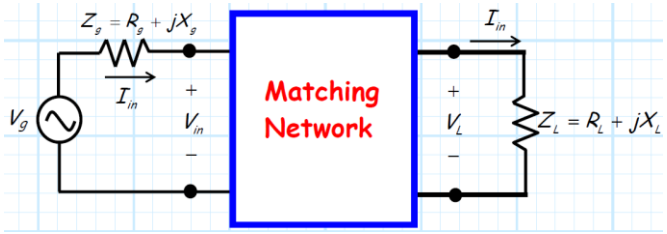
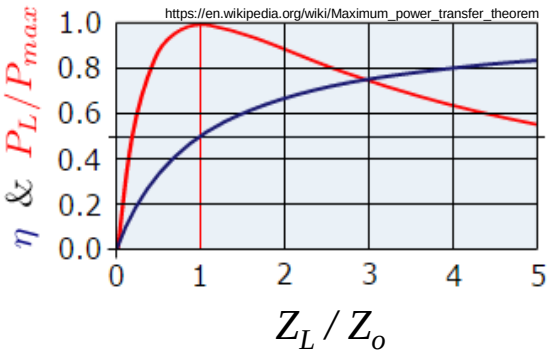
Common & Differential Impedance

Maximum power transfer (power supplied = power delivered) occurs when source and load have matched impedance

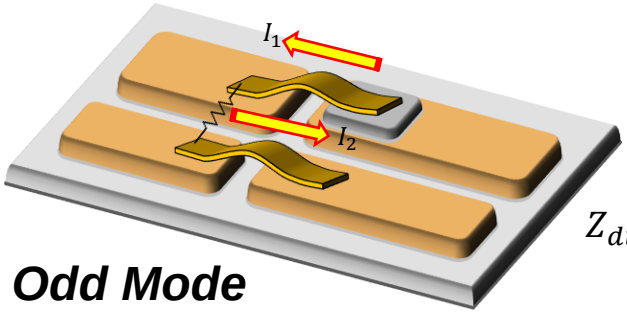


http://www.ittc.ku.edu/~jstiles/723/handouts/section_5_1_Matching_with_Lumped_Elements_package.pdf



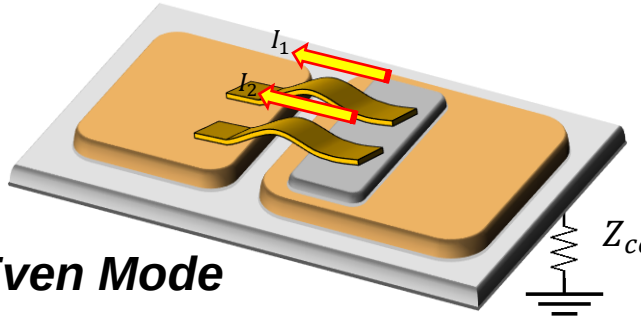
Important to understand the interconnect impedances that make up the "matched network" to reduce losses

→Characteristic impedance shifts due to the influence of even and odd modes creating common/differential impedance to the current path within the module



$Z_{diff} = 2 * Z_{odd}$

Odd Mode



$Z_{common} = {}^{Z_{even}}/_{2}$

Even Mode

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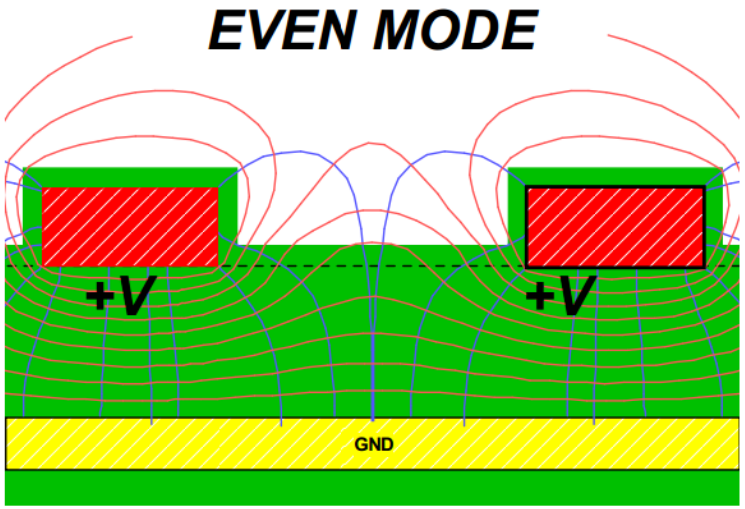
Differential Impedance of Wire/Ribbon Bonds

Common mode noise is a major concern for signal integrity and device stress

- Induced current in nearby victim conductors due to crosstalk generated from aggressor conductors will create an undesirable V_{noise} on the victim interconnect! ($V_{noise} = I_{induced}*Z_{common}$)
- Even mode differential impedance is directly related to Z_{common}

Characteristic impedance of a wire/ribbon bond may be affected by a neighbor bond due to even and odd impedances

- Parallel Wire/Ribbon bonds off a die facilitate **even mode** because all interconnects are driven high & low at same time
- Desire common mode (even mode) impedance to be low!



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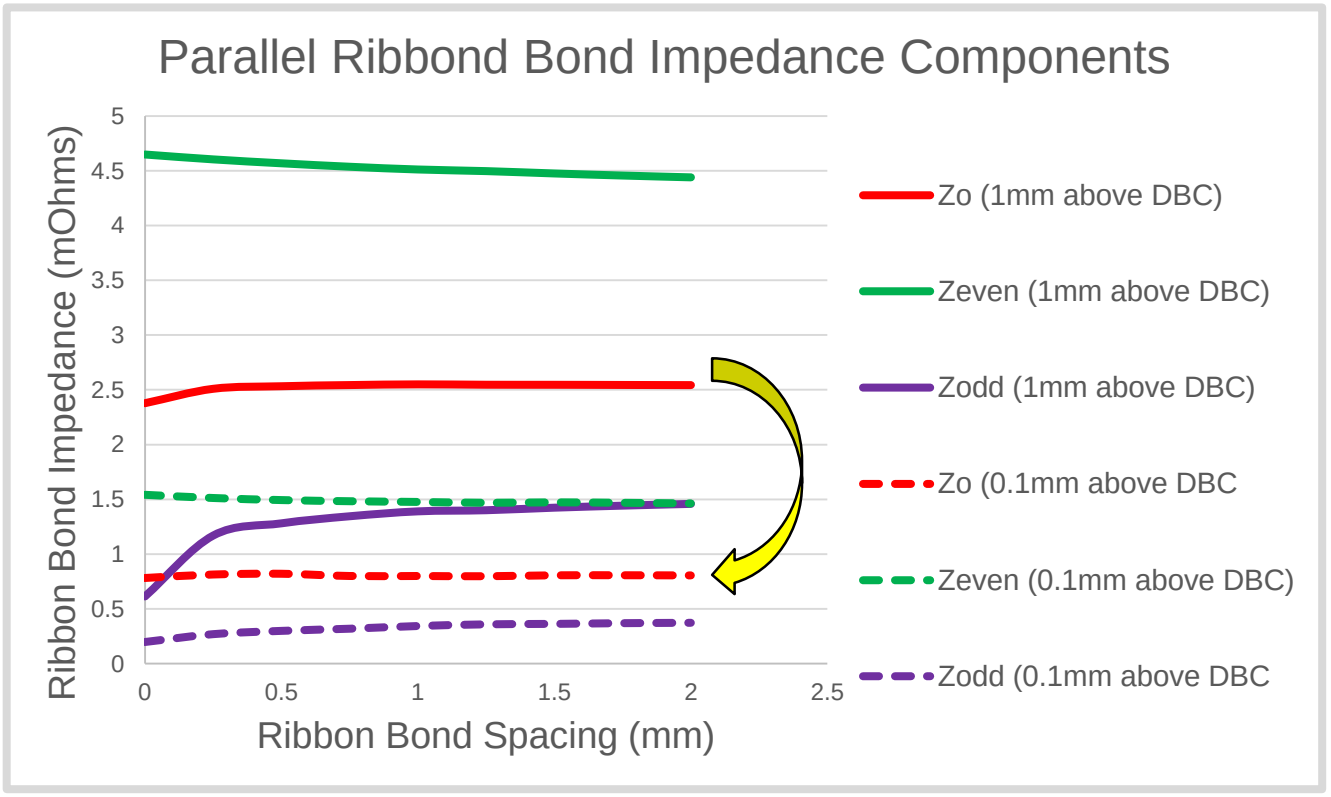
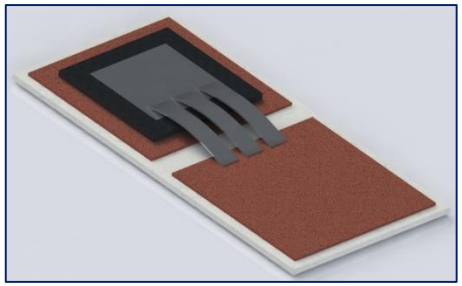
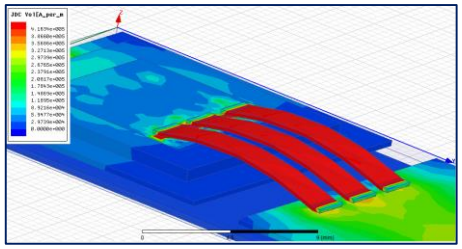
Design for Z_{odd} & Z_{even}

- Want to design for matching impedances to reduce reflections, losses, etc.
- Therefore, Z_{odd} & Z_{even} need to be considered, along with Z_o, during design







Smaller distance between substrate & ribbon bond = smaller impedance components

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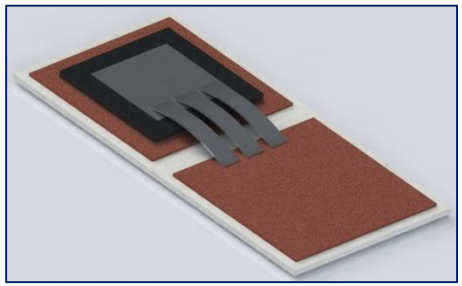
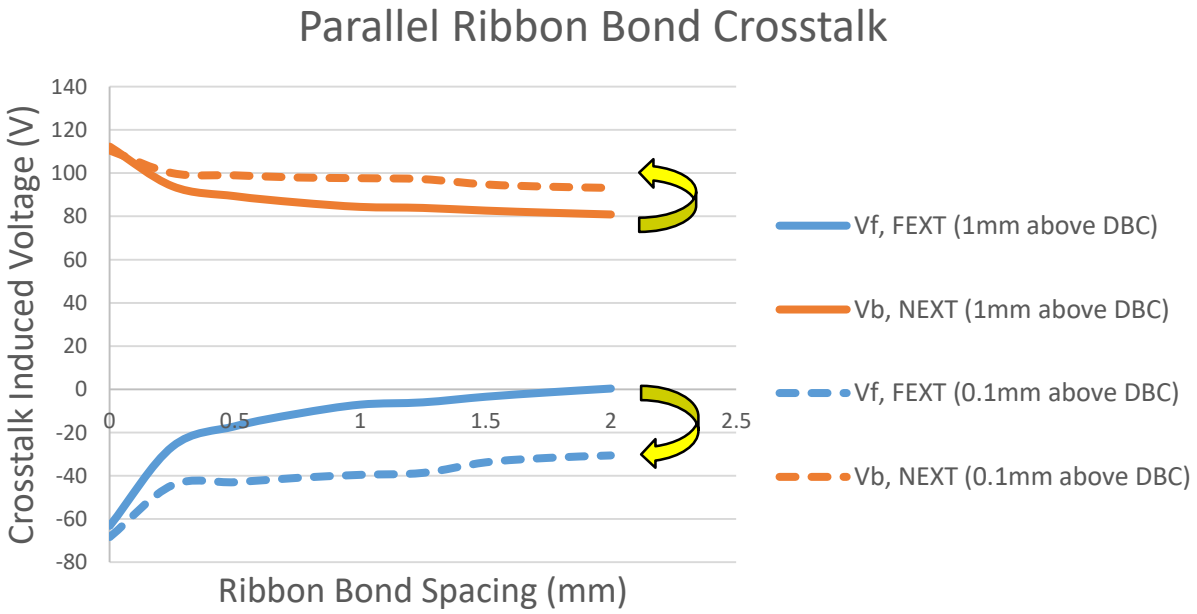
Near-End & Far End X-talk

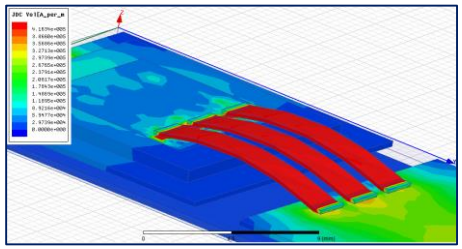
Different crosstalk voltage magnitudes seen at the near and far end of the wire/ribbon bond: V_{NEXT} and V_{FEXT} , respectively

Negative Effects:

- Force uneven current sharing between interconnects due to fluctuation of differential voltage across an interconnect from switching dynamics
- Observe pwr/gnd plane bounce during high *dv/dt* that can cause unnecessary voltage stress on the devices & substrates!







Smaller distance between substrate & ribbon bond = greater crosstalk voltage magnitude

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Design Insight & Summary

- Wire/ribbon bond densities within power modules should be considered to mitigate the negative effects from the fastest rising/fall edge of the voltage and current high frequency components
- True voltage/current waveforms see a “transmission-like” interconnect that has a characteristic impedance comprised of even/odd components
  - Proper characterization of interconnects is essential when attempting to “match” impedances internally within power modules to reduce losses
  - Design for lowest common mode (even mode) impedance as possible to reduce influence of crosstalk voltage between interconnects
- Spacing between parallel interconnects, and interconnect distance above power substrate affects electro-physical coupling within power modules
  - Interconnect impedances decrease with smaller vertical spacing
  - Crosstalk voltage magnitudes:
    - Increase with smaller vertical spacing
    - Decrease with wider interconnect pitch

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Future Work

North Carolina State University & Hesse partnership for:

- Validation of simulation results through fabrication and testing of power substrates and copper flexible welded interconnects
- Compare performance of copper and aluminum wire and ribbon through interconnect density variations
- Apply to VHF-based resonant converters that are capable of achieving unprecedented power densities through WBG power semiconductors
- Compare high frequency, high power density performance between WBG and Si arrangements, from double-pulse to full-power test platforms

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