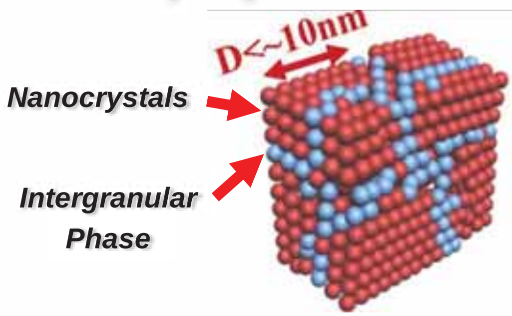
NATIONAL ENERGY TECHNOLOGY LABORATORY



Emergence of WBG Based Power Electronics and System Level Needs / Opportunities for Advances in Passives, Packaging, and Peripherals with Emphasis on HF Magnetics

Dr. Paul Ohodnicki, Materials Scientist / Team Lead

Electrochemical and Magnetic Materials Team
Functional Materials Development Division
NETL Office of Research and Development

Overview of Presentation

- Historic Thrust in Active Components for WBG-Based Power Electronics
  - Promise of WBG-Based Semiconductors Relative to Si
  - Technical / Cost Progress Driven By Sustained Government Investment
  - Commercial and Near-Commercial Devices Reaching Maturity

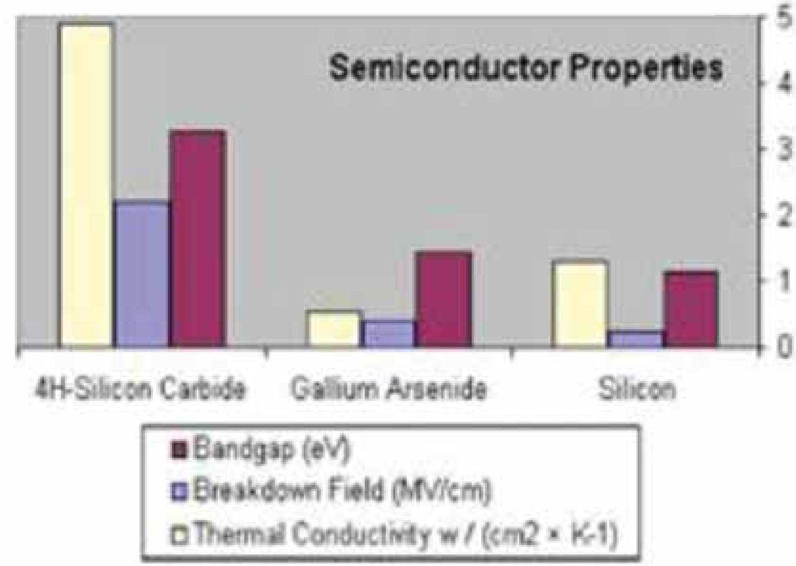
- Systems Level Needs for WBG-Based Power Electronics
  - Systems Levels Design Issues (Harmonics, EMI, Parasitics)
  - Thermal Management
  - Advances in Passive Components (Packaging, Capacitors, Magnetics)

- Needs and Opportunities for Research in HF Magnetics
  - Existing and Emerging Materials for HF Inductors / Transformers
  - Advanced Inductor / Transformer Fabrication and Design
  - Novel Power Conversion Topologies Leveraging HF Transformers

- Summary and Conclusion

Historic Thrust in Active Components for Wide Bandgap Semiconductor Based Devices

Technical Advantages of WBG Semiconductor Devices



Device	BV (kV)	500 Hz 5 kV $P_{sw,sp}$ (W/cm²)	5 kHz 5 kV $P_{sw,sp}$ (W/cm²)	20 kHz 5 kV $P_{sw,sp}$ (W/cm²)	33 A/cm² 50% Duty 100°C $P_{cond,sp}$ (W/cm²)
SiC DMOSFET	10	4	40	160	100
SiC n-IGBT	12	6.5	65	260	66
Si IGBT	2x 6.5	72.5	725	2900	182

New Materials Enable Revolutionary Device / System Level Advances!

- → Higher Reverse Voltages
- → Higher Switching Frequencies
- → Higher Temperature Operation
- → Increased Thermal Conductivity
- → Lower On-State Losses

Converter Topology Simplification

Higher Efficiency

Increased Power Density

Reduced Thermal Management Load

Courtesy of G. Nojima, Eaton Corporation

Sustained Government Investment in WBG-Based Devices

Example Major WBG Development Programs:

→ DARPA WBG High-Power Electronics (HPE)

→ Air Force Office of Scientific Research

→ Office of Naval Research Advanced Electrical Power Systems (AEPS)

→ Army Research Laboratory

→ National Aeronautics and Space Administration (NASA)

→ NIST Semiconductor Electronics Division

→ National Science Foundation (VA Tech CPES)

Major Cost Reductions Result from 3 Factors

– Higher Quality SiC Material

– Larger Production Volumes

– SiC Wafer Diameter Increased From 3" to 100"

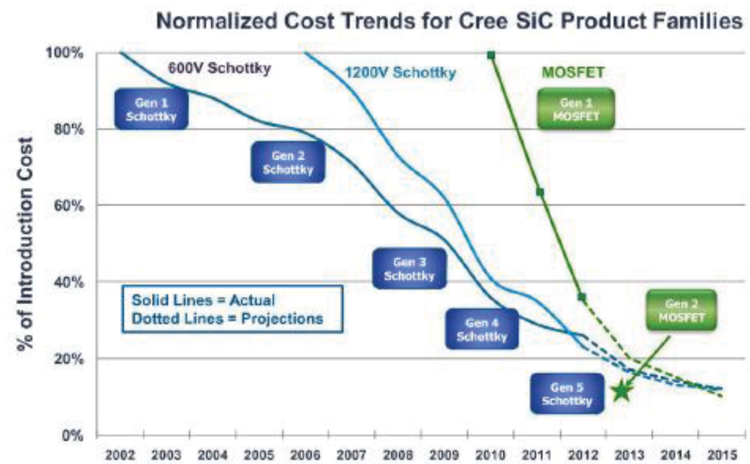


Figure 3. Decline of device cost for Cree SiC products over time (Hull, 2013)

From: Wide Bandgap Power Electronics Technology Assessment:

DOE Quadrennial Technology Review, Chapter 8, Draft

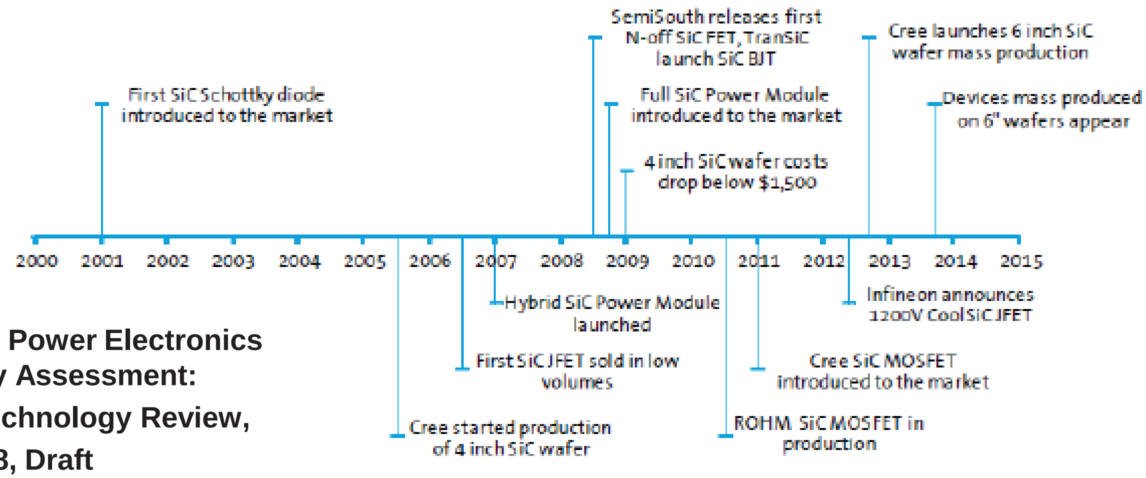
Most Recently within DOE:

→ DOE ARPA-E Switches (2014)

→ DOE EERE AMO PowerAmerica (2014)

Motivated by the Promise and Potential for WBG-Based Devices, Semiconductor Materials and Associated Devices Have Seen Sustained and Significant Government Funding Over Time.

SiC-Based Commercial and Near-Commercial Devices



From: Wide Bandgap Power Electronics Technology Assessment:

DOE Quadrennial Technology Review, Chapter 8, Draft

Figure 2. Milestones in SiC power electronics development (Eden, 2013)

Table 1. Distribution of 2010 silicon carbide power electronics device revenues by company and fab location (Yole Developpement, 2012).

Company	2010 SiC Power Electronics Revenue (Million $)	Headquarter	Fab location
Infineon	$27.1	Germany	Villach, Austria
Cree Technologies	$19.7	U.S.A	Durham, NC, U.S.A
STMicro	$1.6	Switzerland	Catania, Italy
Rohm	$1.1	Japan	Fukuoka, Japan and Miyazaki, Japan
All others	$3.7		
Total	$53.2		

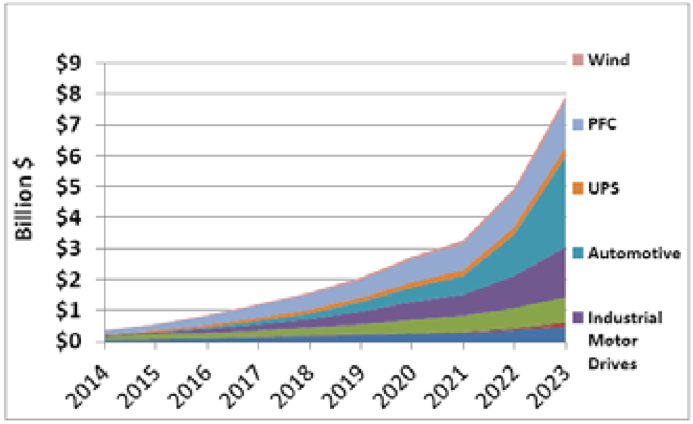
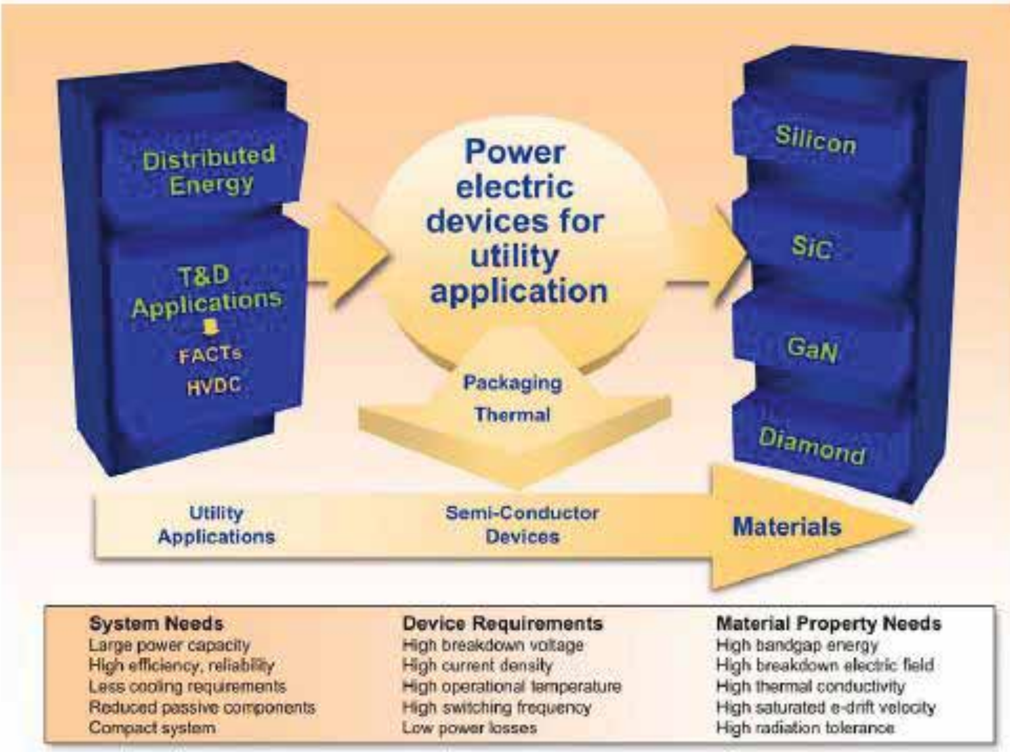


Figure 1. Projected sales for WBG power electronic devices (Eden, 2013)

SiC-Based Switching Devices Have Been Commercialized with More Expected on the Horizon. Market Projections for WBG-Based Power Electronics are Highly Optimistic Suggesting Significant Growth Potential.

System Level Needs for WBG-Based Power Electronics

Future Promise of Grid-Scale WBG-Based Power Electronics



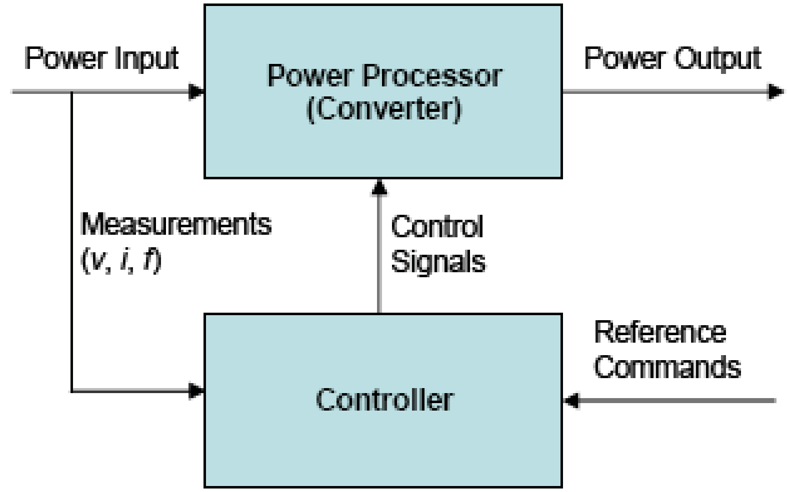


Fig. 1.1. Block diagram of a power electronic system.

POWER ELECTRONICS FOR DISTRIBUTED ENERGY SYSTEMS AND TRANSMISSION AND DISTRIBUTION APPLICATIONS

Publication Date: December 2005

ORNL/TM-2005/230

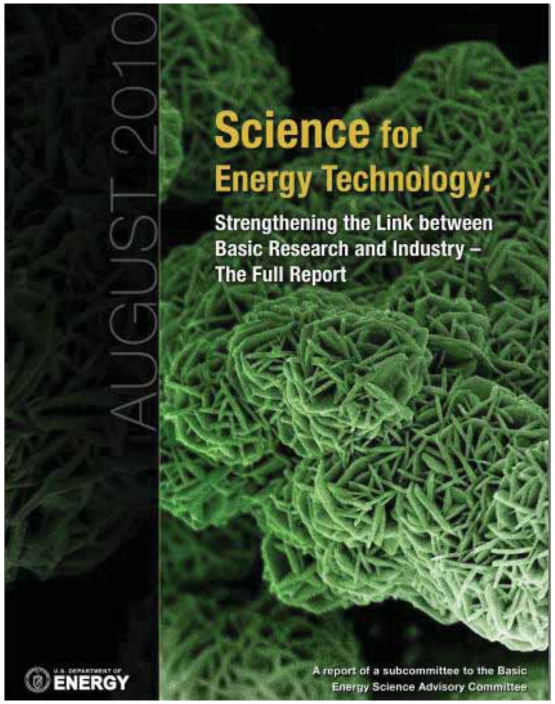
WBG-Based Power Electronics Show Significant Potential for Emerging T&D / Grid Related Applications Including:

→ Distributed Energy Grid Integration (PV, Fuel Cells, ES, EV, Microturbine)

→ Power Flow Controllers for T&D Applications (FACTS, HVDC)

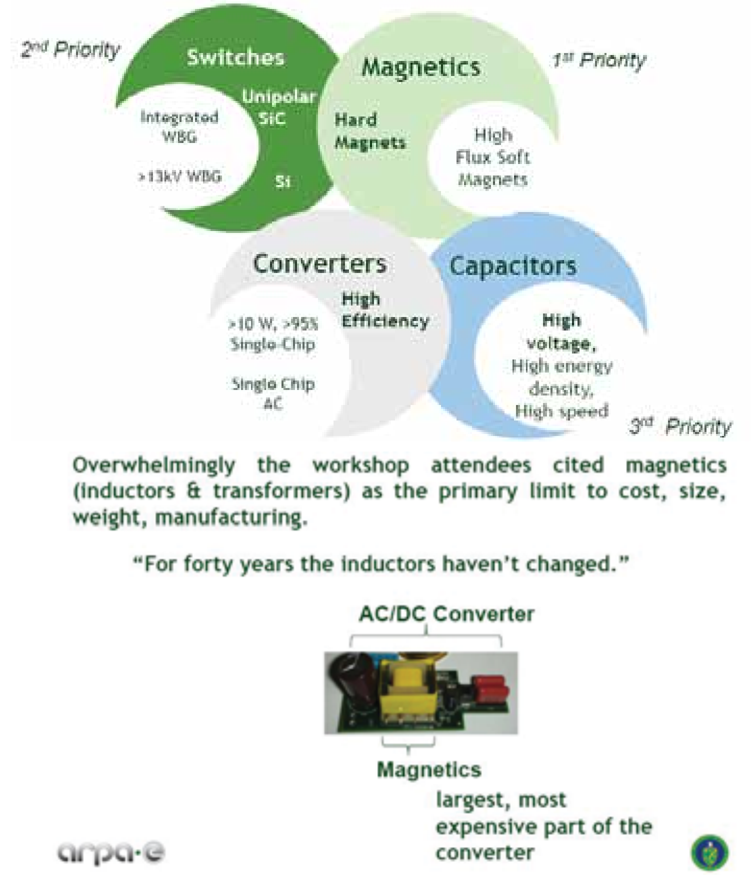
WBG Switching Devices ≠ WBG-Based Power Electronic Systems!

Needs for Advanced Power Electronic Materials



Basic Energy Sciences 2010 Report: Emphasis on Grid Technologies

Key Research Priority: Power Electronic Materials



ARPA-E 2010 Workshop: Soft Magnetic Materials for Inductors Highest Priority for Their Program Due to Historic Lack of Federal Investment.

www.arpa-e.energy.gov

Needs for Advanced Power Electronic Materials

TMS2015
144th Annual Meeting & Exhibition

March 15-19, 2015 • Walt Disney World
Orlando, Florida, USA

Organized by:
Paul Ohodnicki, National Energy Technology Laboratory (USA)
Michael Lanagan, Penn State University (USA)
Michael McHenry, Carnegie Mellon University (USA)
Rachael Myers-Ward, Naval Research Laboratory (USA)
Clive Randall, Penn State University (USA)
Matthew Willard, Case Western Reserve University (USA)

Advanced Materials for Power Electronics, Power Conditioning, and Power Conversion III

Independent of the means by which electrical power is generated (conventional fossil, advanced fossil, nuclear, solar, wind, etc.), power conditioning and conversion is required to transform power into an appropriate form for efficient and cost-effective integration into the grid. By 2030, it is also projected that 80% of all electricity will flow through power electronics. Advanced materials including soft magnetic materials, semiconductors, and dielectric materials for capacitors are crucial for enabling the next generation of advanced power electronics technologies.

These technical communities have historically worked independent of one another, and materials development efforts have often been carried out in the absence of frequent and meaningful interactions with the power electronics community. The proposed symposium aims to bridge these historical gaps through a number of technical symposia devoted to relevant materials systems including soft magnets, dielectric materials for capacitors, and semiconductor materials. The primary focus of the proposed symposium will be in the area of advanced materials for power electronics and power conditioning systems. A range of invited and contributed talks will be presented by the top materials scientists in each field. To supplement the traditional technical sessions, a selected group of technical experts from the power electronics community will also be invited to present and to engage the materials community. These invited talks are intended to promote interactions between the materials and power electronics communities, to educate the materials community about critical materials needs, and to educate the power electronics community about state-of-the-art material developments.

We Have Recently Organized a New Symposium at TMS Annual 2012-2015 Meetings to Help Address these Emerging Needs.
Soft Magnetic Materials, Semiconductors, Capacitors, and Packaging Materials were All Included in the Programming

http://www.tms.org/meetings/annual-15/AM15home.aspx

Systems-Level Challenges to Fully Leverage WBG Devices

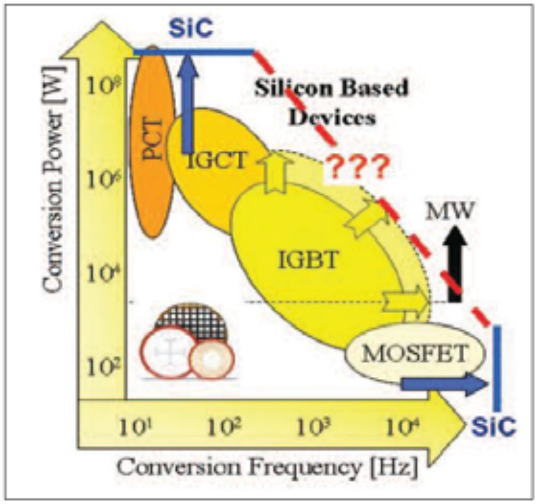


Figure 1: Power semiconductors and their power and frequency range in MW PE applications

"Wide Bandgap Power Devices in Megawatt Applications"
www.power-mag.com
Issue 4, 2012,
Power Electronics Europe

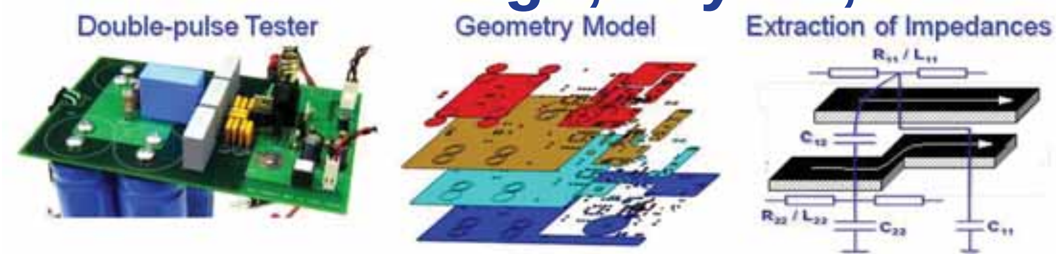
Technical Challenges at Converter / System Level

- **Increasing Frequencies of High-Voltage / Power Devices:**
  - Parasitic Inductances / Capacitances
  - EMI Effects Due to Stray Fields / Harmonics
  - Increased Losses of Inductors / Magnetics
- **Reduced Volume / Increased Power Density**
  - Higher Temperature / Frequency of Passives
  - Thermal Management
  - Electrical Contacts, Bonding, and Packaging

Systems-Level Issues, Passives, and Peripherals Have Not Experienced the Same Sustained R&D Funding / Focus as WBG Switching Devices.

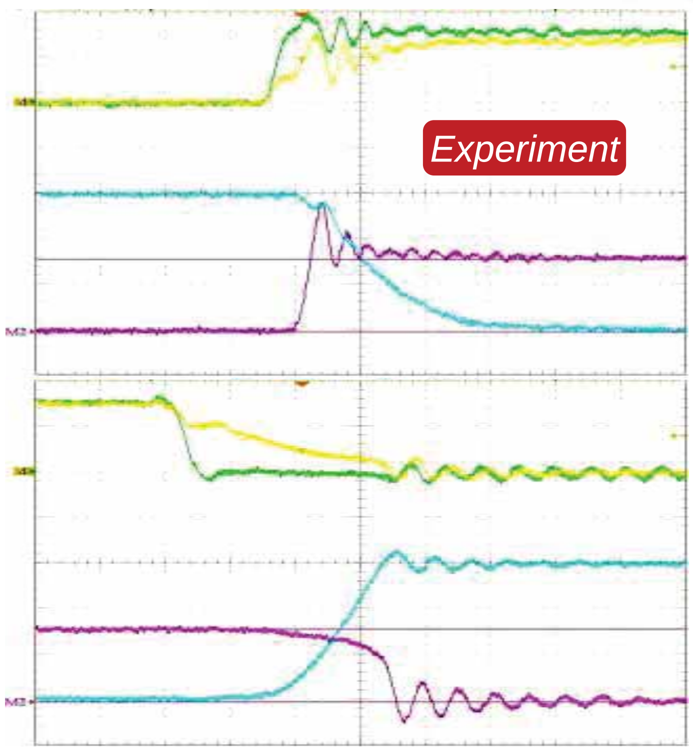
Major Opportunities and Needs Exist for New Materials Innovations!

Systems-Level Design, Layout, and Modeling



Turn-on

Turn-off

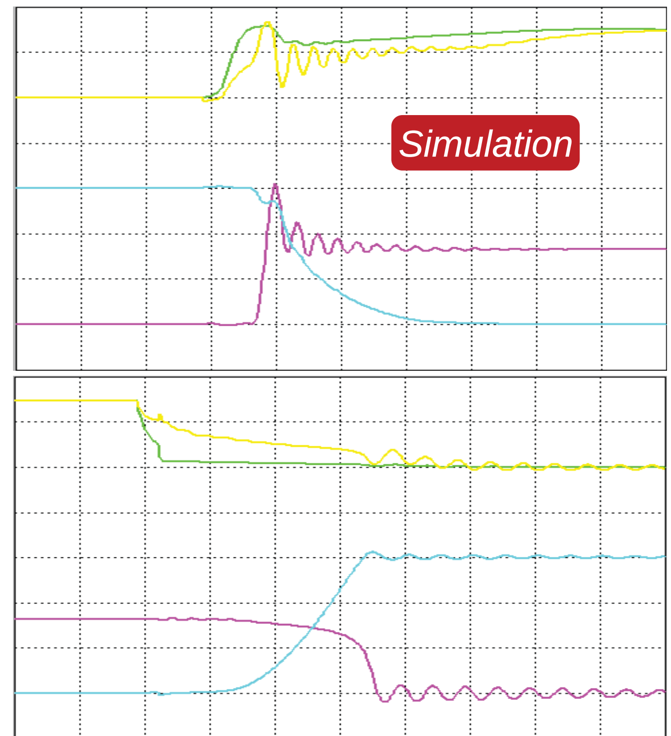


V_{drive} (10 V/div)

V_{gs} (10 V/div)

V_{ds} (200 V/div)

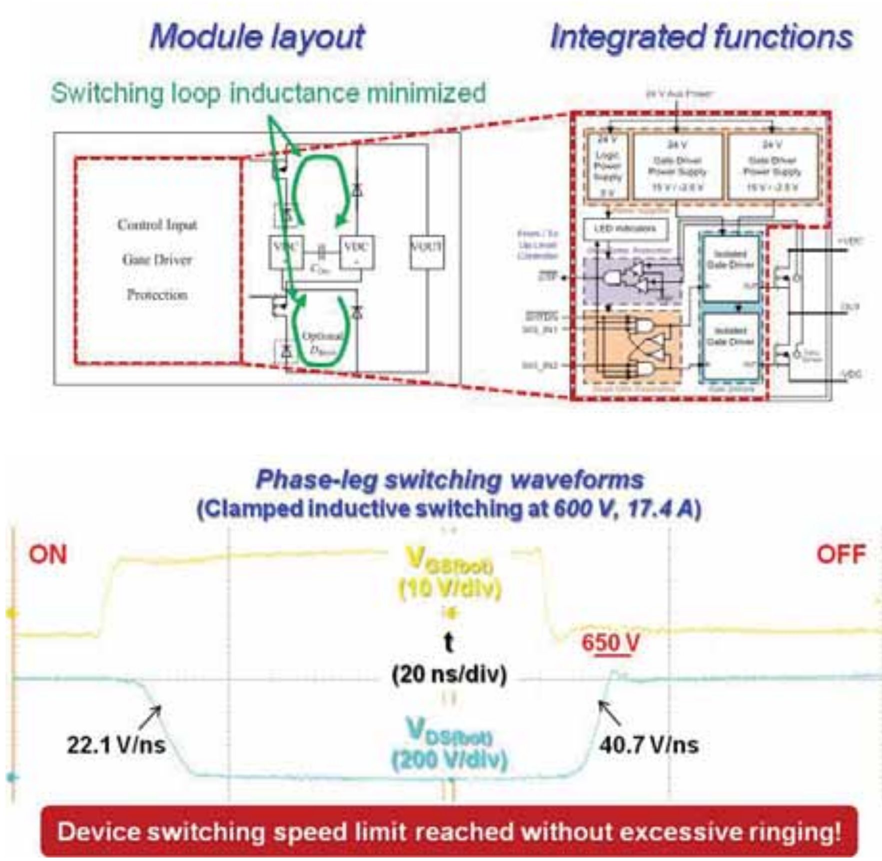
I_d (5 A/div)

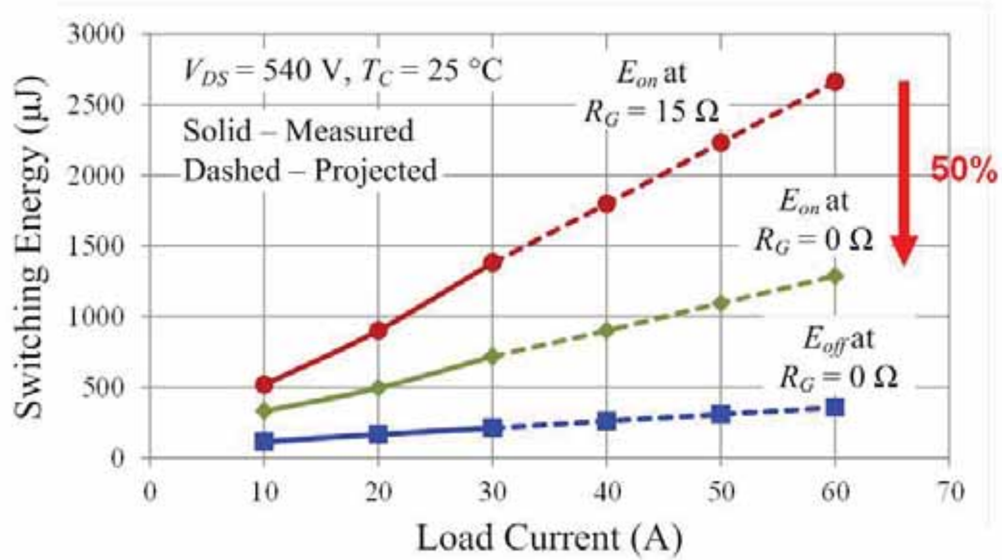


Parasitic Inductances and Capacitances Associated with Circuit Design Can Cause Oscillatory Behavior and "Ringing" During WBG-Switching. Advanced Component Design and Layout Can Address and Mitigate.

Courtesy of VA Tech CPES, HDI Consortium

Systems-Level Design, Layout, and Modeling





Smaller switching energy can be achieved without compromising to the parasitic ringing.

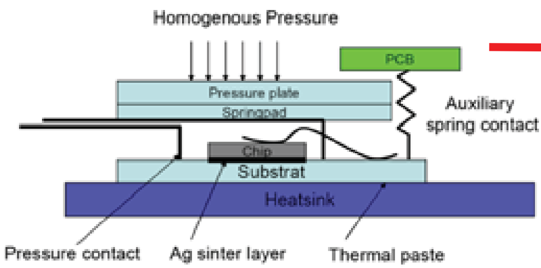
For Example, Through Advanced WBG Converter Module Layout Switching Loop Inductance Can Be Minimized.

Reduced Ringing and Switching Energies are Achieved as a Result!

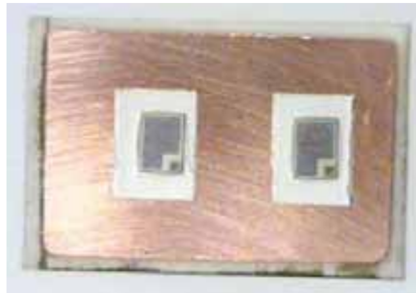
Courtesy of VA Tech CPES, HDI Consortium

Systems-Level Packaging and Thermal Management

Bonding, Packaging, and Thermal Management



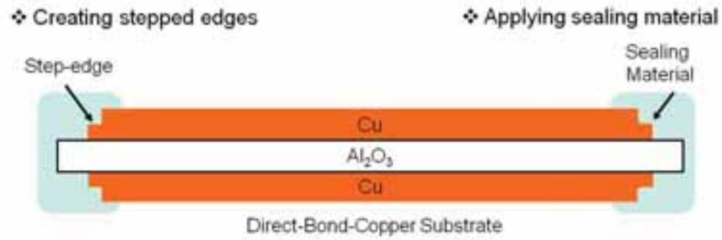
Ag sintering based die-attachment



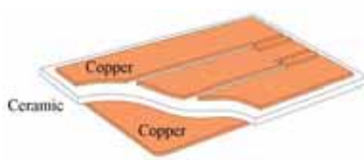
Sintering of nanoAg paste to Reduce P. / Temp. Requirement.

Sealing / Packaging

Now ~1200 Cycles to Failure!



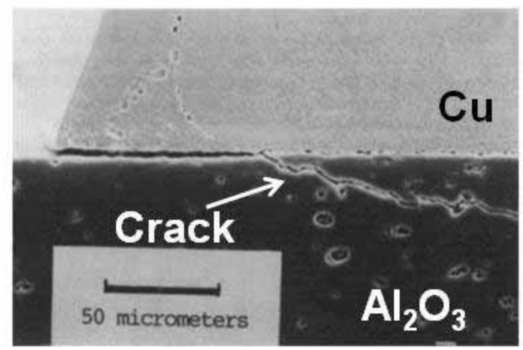
Repeated Cycling from -50 to 200°C, Direct Bond Copper Substrate Fails



Before temperature cycling

After temperature cycling

< 20 cycles



Materials Innovations Can Improve Bonding Strength at Elevated Temps., Performance, Processability, and Thermal Management.

Packaging, Substrates, Bonding Impacts on Parasitics Need Considered!

Courtesy of VA Tech CPES, HDI Consortium

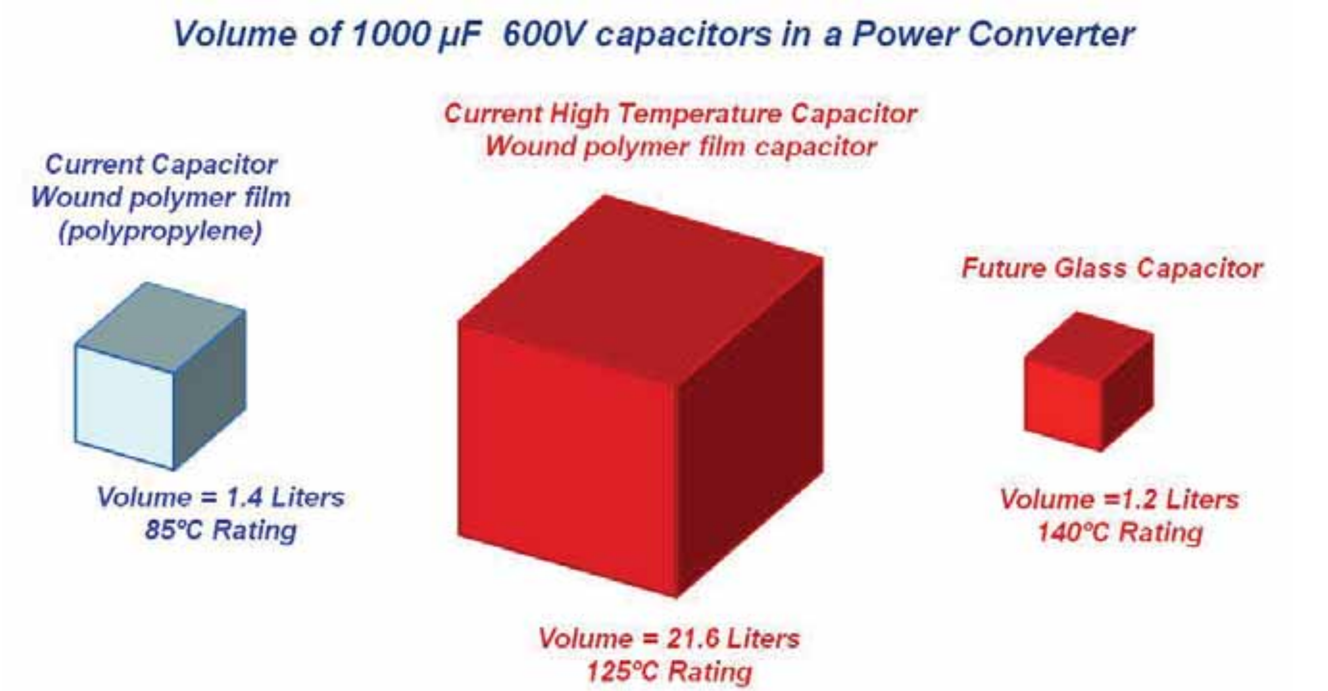
Advanced Passives for WBG-Based Power Electronics

$$Energy = \frac{1}{2} C V^2$$

Capacitance — Voltage — **Joules**

$$Energy\_density = \frac{1}{2} \varepsilon_o \varepsilon'_r \vec{E}^2$$

Permittivity — Electric Field — **Joules / cm^3**

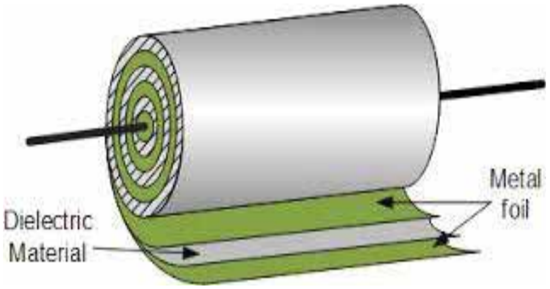


For Capacitors, Higher Operational Temperatures While Retaining Sufficient Energy Densities Requires Advances in Capacitor Materials.

Glasses are Potential Materials of Interest for Higher Temperatures.

Courtesy of Prof. Michael Lanagan, PSU Center for Dielectrics

Advanced Passives for WBG-Based Power Electronics



Typical Polymer Film Capacitor

Replace with Other Dielectrics?

Coiled glass capacitor fabricated at Penn State by spraying Ag ink on the glass ribbon and then winding the ribbon around a mullite mandrel.
Right side: free standing glass ribbon section
Left side: fully packaged coiled glass capacitor

Environmental Chamber

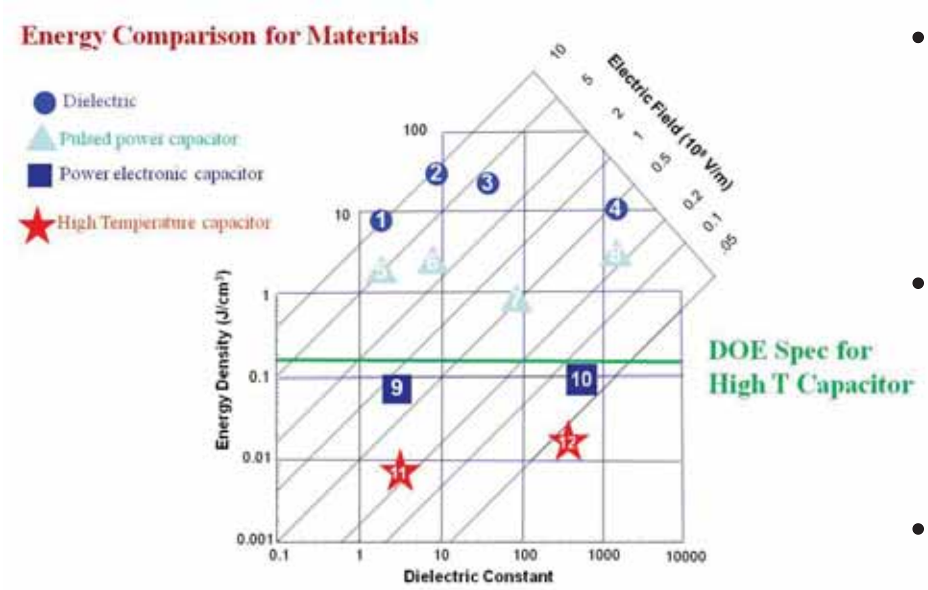
Coiled Capacitor

Temperature	Frequency	Capacitance, nF	Loss
50°C	1 KHz	67.2	0.001
	10 KHz	67.1	0.002
100°C	1 KHz	67.6	0.004
	10 KHz	67.4	0.003
150°C	1 KHz	68.2	0.005
	10 KHz	67.9	0.003

Examples of High Temperature Capacitors Fabricated Using Commercially Available Glass as the Dielectric Materials Showing Good Performance.

Courtesy of Prof. Michael Lanagan, PSU Center for Dielectrics

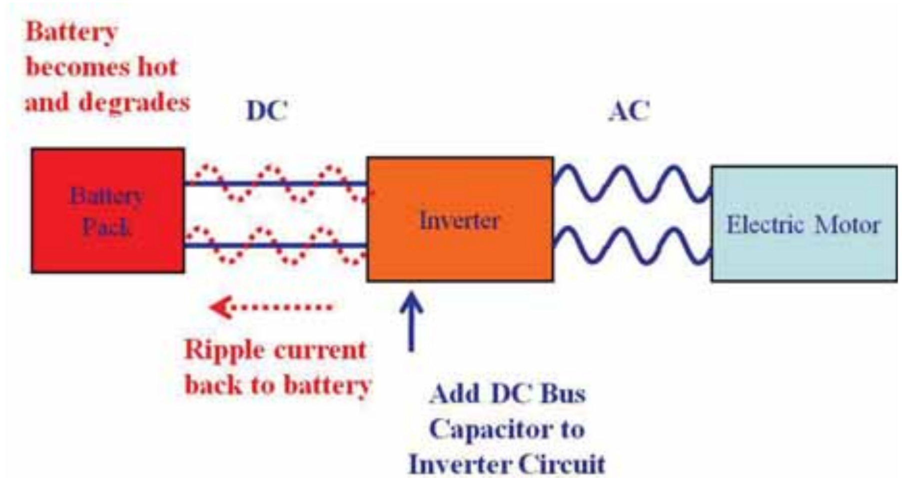
Advanced Passives for WBG-Based Power Electronics



(1) Polypropylene, (2) Alkali-free Barium Boroaluminosilicate Glass, (3) Fluoropolymer, (4) PZT Ceramics, (5) Polypropylene Capacitor (6) High-k Polymer Capacitor, (7) NPO MLCC, (8) X7R based MLCC, (9) Polypropylene film capacitor, (10) X7R MLCC, (11) High Temperature, 125°C, Polymer Capacitor, (12) High Temperature, 200°C, MLCC

- **Multilayer Ceramic Capacitors:**
  - Excellent high temperature performance
  - Smaller than film caps
  - Lack self-healing behavior
- **Polymer Film Capacitors**
  - Excellent performance and size
  - Self-healing capability
  - Low ripple current at high temperature
- **Glass Capacitors**
  - High temperature performance, self healing

DC Bus Capacitors are a Key Application for Variable Frequency Drives, Electric Motors, etc.



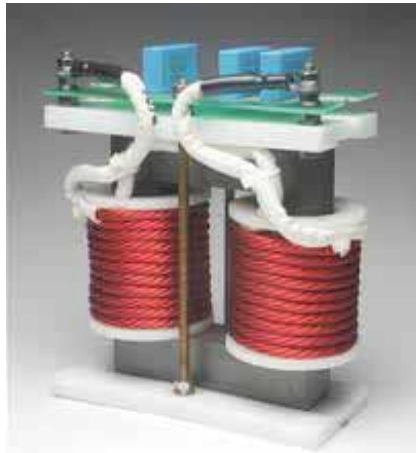
Relevant Targets for High Temperature and High Performance Capacitors in Various Applications are Illustrated.

Courtesy of Prof. Michael Lanagan, PSU Center for Dielectrics

Advanced Passives for WBG-Based Power Electronics

<u>60Hz vs 20kHz</u>

330kVA 60Hz Transformer
55" high and 2700Lb



250kVA 20kHz Transformer
16" high and 75Lb

15kV Class > 1MVA Transformer Frequency	Fx to 60Hz Ratio	Transformer Core Mass Reduction Factor	Transformer Core Volume Reduction Factor
60Hz	1	1	1
400Hz	7	8	1.4
1kHz	17	10	1.7
20kHz	333	68	34
50kHz	833	82	34

Faraday's Law of induction:

$$\epsilon = -d\Phi/dt$$

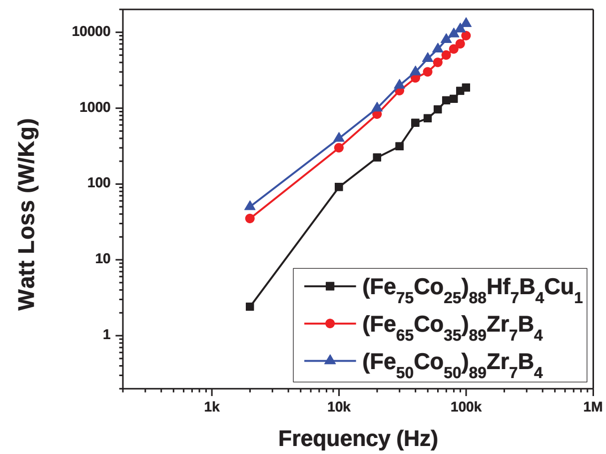
electromotive force → ϵ; time-changing Magnetic flux → $d\Phi/dt$

$$\Phi = \mathbf{B} \cdot \mathbf{A}$$

flux density (induction) → Φ; area → $\mathbf{A}$

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$$

permeability of free space → μ_0; magnetic field → $\mathbf{H}$; magnetization → $\mathbf{M}$



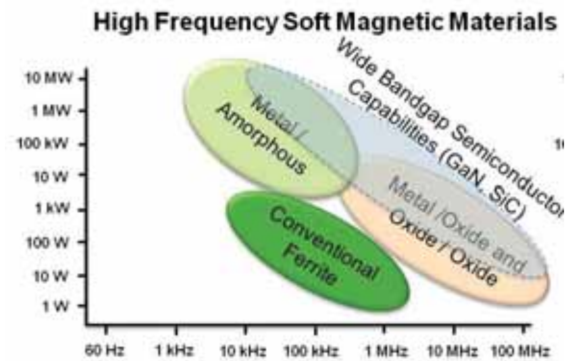
$$P_t = kf^{\alpha}B^{\beta}$$

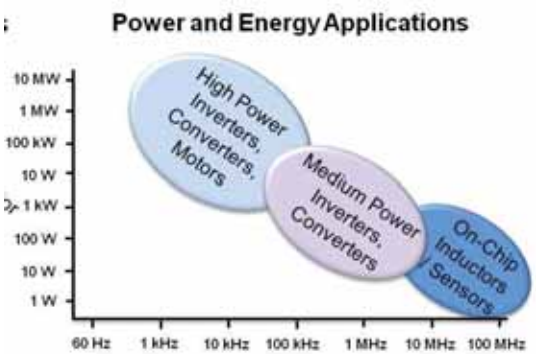
Increased Losses at Elevated Frequency
(Eddy Currents)

High Frequency / High Temperature Magnetics is a Materials Challenge, But Large Volume Reductions are Possible (Inductors, Transformers).

Courtesy of G. Nojima, Eaton Corporation and A. Leary, Carnegie Mellon

Relevant Classes of Soft Magnetic Materials





Ferrites:

→High Resistivity Limits Eddy Current Losses

→Saturation Induction Limits High Power Application

Classes of Materials	Relevant Frequency Range	Maximum Saturation Induction (T)	DC permeability	Resistivity (Ω – cm)	Useful Temperature Range (C)
Bulk Metallic Alloys	DC – 1kHz	2.5	10^2 - 10^5	0.5×10^{-6}	<500
Powder Core	10 – 500kHz	1.6	20 - 500	1	<200
Ferrites	10kHz – 100MHz	0.5	100 - 5000	$10^2 - 10^8$	<300
Amorphous Alloys	DC - 100kHz	1.5	10^5	130×10^{-6}	<200
Nanocomposites	DC - 100kHz	1.9	10^0 - 10^5	110×10^{-6}	<400

Major Area of Emphasis for NETL and Collaborators

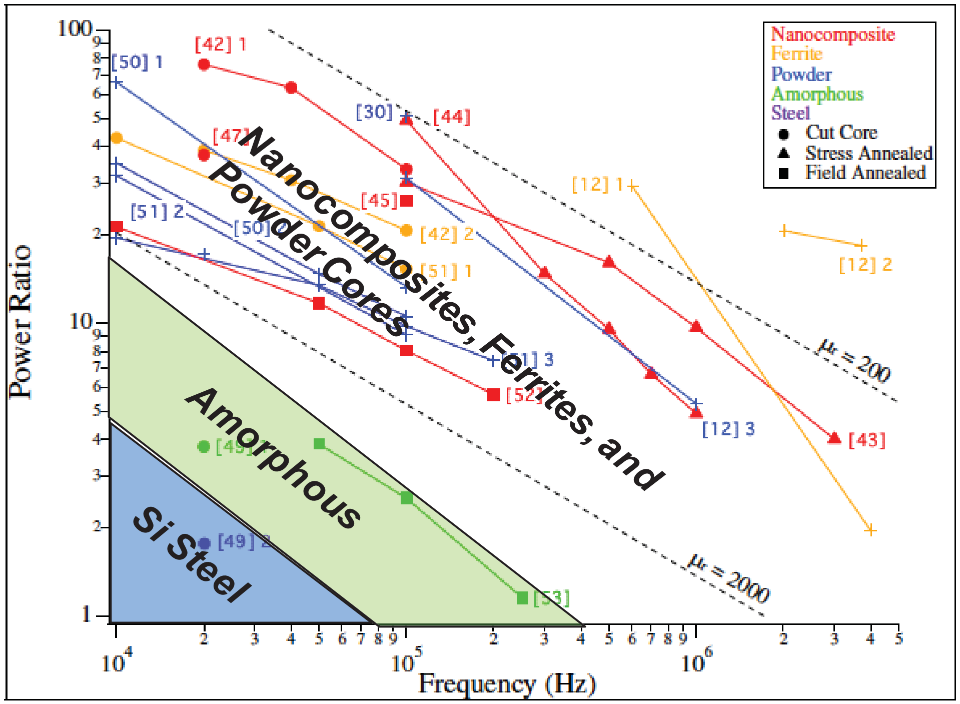
Bulk Metallic Alloys are Too Lossy at kHz Frequencies for WBG Power Electronics, and Powder Cores Introduce EMI and Parasitics (Stray Fields).

Amorphous and Nanocomposite Magnets Have Ideal Combinations of Saturation Induction and Losses for High Power, HF Applications and Also Higher Efficiency than Many Si-Steels Even For 60Hz Transformers.

Soft Magnetic Materials for High Power and Frequency

"Soft Magnetic Materials in High-Frequency, High-Power Conversion Applications"

A. Leary, P. Ohodnicki, and M. McHenry, JOM, Vol. 64 #7 pp. 772-781 (2012).



$$PowerRatio = \frac{Stored\ Power}{Power\ Loss} = \frac{\frac{1}{2}B_m H 2f}{1000k f_{kHz}^{\alpha} B_m^{\beta}}$$

$$Stored\ power\left(\frac{W}{m^3}\right) = BHf = \frac{B^2}{\mu}f$$

$$\eta = \frac{Stored\ power - Power\ loss}{Stored\ power}$$

Reference	Author	Material
[12] 1	Li et al., 2010	MnZn Ferrocube 3F51
[12] 2	Li et al., 2010	NiZn Ferrocube 4F1
[12] 3	Li et al., 2010	Cool Mu
[49] 1	Rylko et al., 2010	METGLAS 2605SA1
[49] 2	Rylko et al., 2010	JFE 10JNHF600
[42] 1	Fukunaga et al., 1990	FINEMET FT-1M cut core
[42] 2	Fukunaga et al., 1990	Ferrite TDK H3ST cut core
[43]	Yanai et al., 2008	Stress annealed FINEMET
[47]	Long et al., 2008	Cut core FeCo HTX-002
[30]	Rylko et al., 2009	MPP 26 Powder
[44]	Fukunaga et al., 2002	Stress annealed FINEMET
[50] 1	Yoshida et al., 2000	Amorphous $Fe_{70}Al_5Ga_2P_{9.65}C_{5.75}B_{4.6}Si_3$ Powder
[50] 2	Yoshida et al., 2000	Mo-Permalloy Powder
[51] 1	Endo et al., 2000	Mn-Zn Ferrite
[51] 2	Endo et al., 2000	$(Fe_{0.97}Cr_{0.03})_{76}(Si_{0.5}B_{0.5})_{22}C_2$ Amorphous powder
[51] 3	Endo et al., 2000	Sendust
[45]	Yoshizawa et al., 2003	Field annealed $Fe_{8.8}Co_{70}Cu_{0.6}Nb_{2.6}Si_9B_9$ nanocomposite
[52]	Kolano-Burian et al., 2008	Field annealed $Fe_{14.7}Co_{58.8}Cu_1Nb_3Si_{13.5}B_9$ nanocomposite
[53]	Martis et al., 1994	METGLAS 2705M

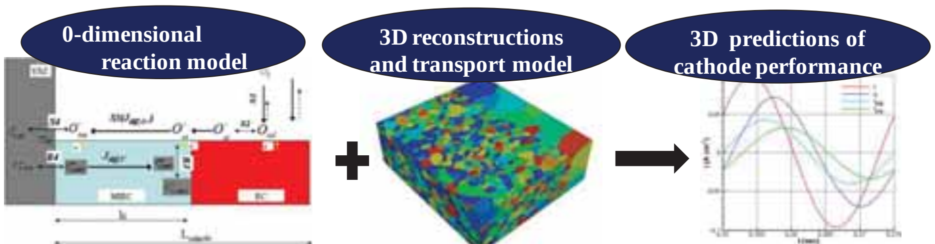
Materials Performance for High Power and High Frequency Inductor Applications Can Be Compared Through a "Power Ratio" Defined as Noted Above.

The "Power Ratio" Does Not Include Considerations of Parasitics, EMI, and Harmonics Important for WBG Power Electronics Which Must Be Measured at a "System" and/or "Component" Level.

Soft Magnetic Material and Device Research of NETL and Collaborators

NETL Electrochemical and Magnetic Material Team

Current Fiscal Year 2015



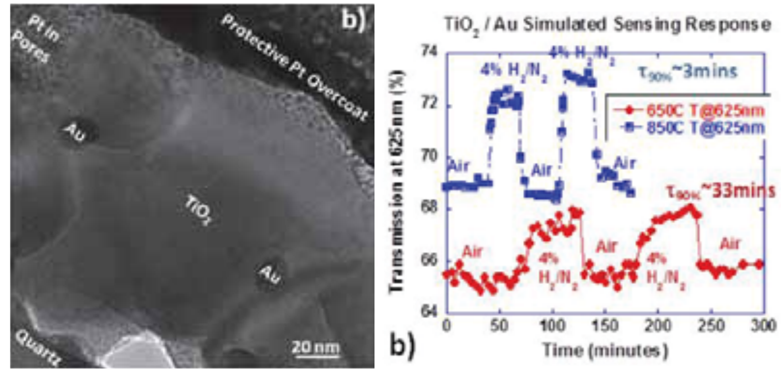
Solid Oxide Fuel Cell Devices

Modeling + Characterization → Optimal Device Performance

Solid Oxide Fuel Cell Materials

Function and Durability
(DOE FE SECA Program)

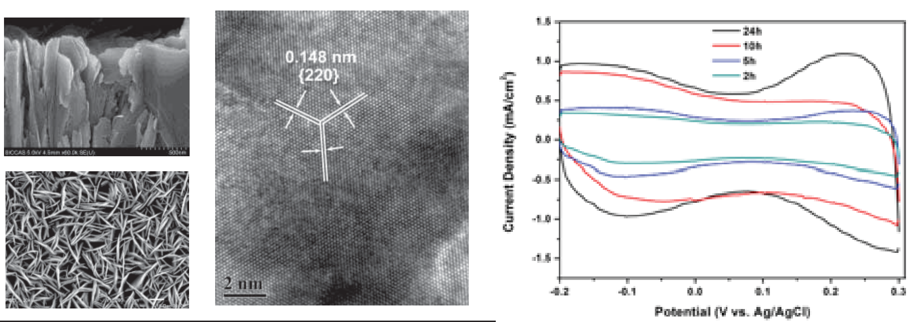
Current Fiscal Year 2015



Sensor Materials

Chemical and Temperature Sensing
(DOE FE Cross-Cutting Program, Others)

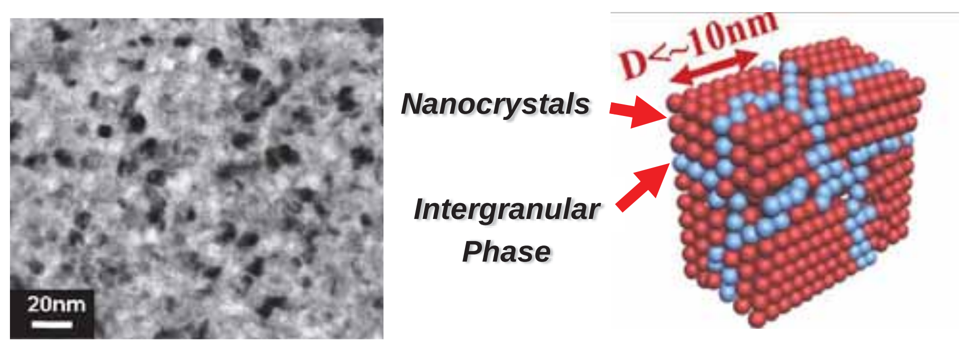
Ended Fiscal Year 2014



Energy Storage Materials

(DOE EERE Program)

Current Fiscal Year 2015



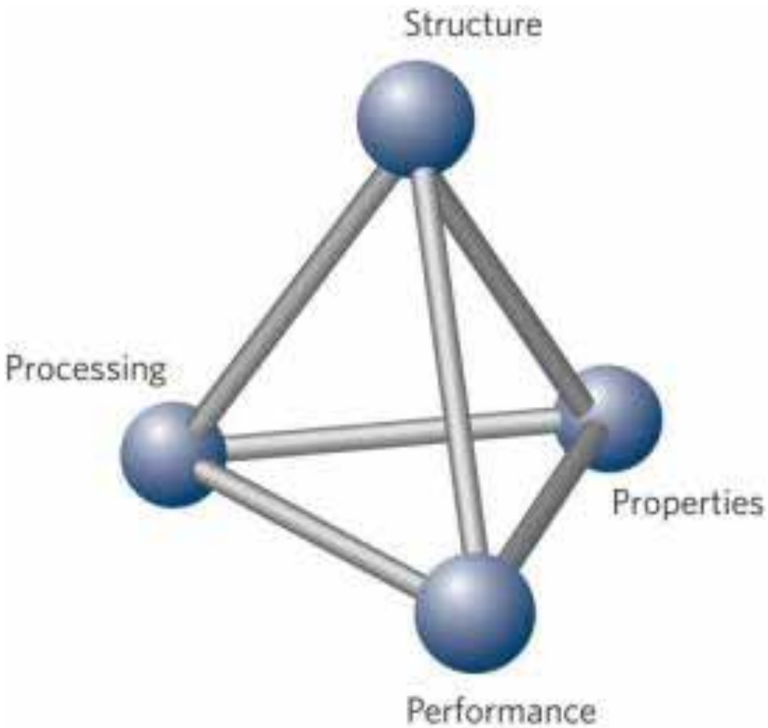
Soft Magnetic Materials

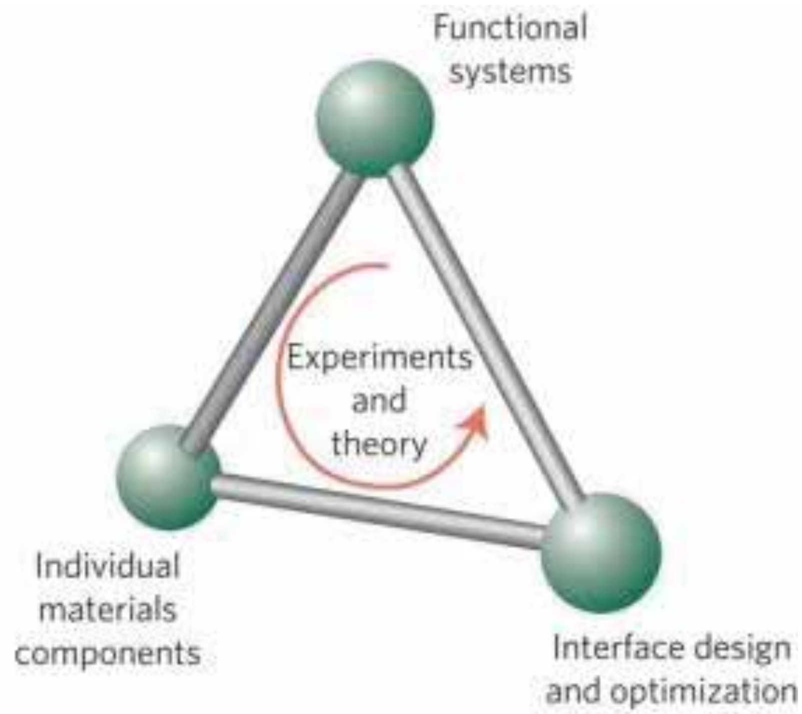
Inductors and Sensors
(ARPA-E, URS, Others)

Materials and Device Development Emphasis

Classic Materials Science Paradigm

Emerging Paradigm Materials Interface with Functional Systems and Devices



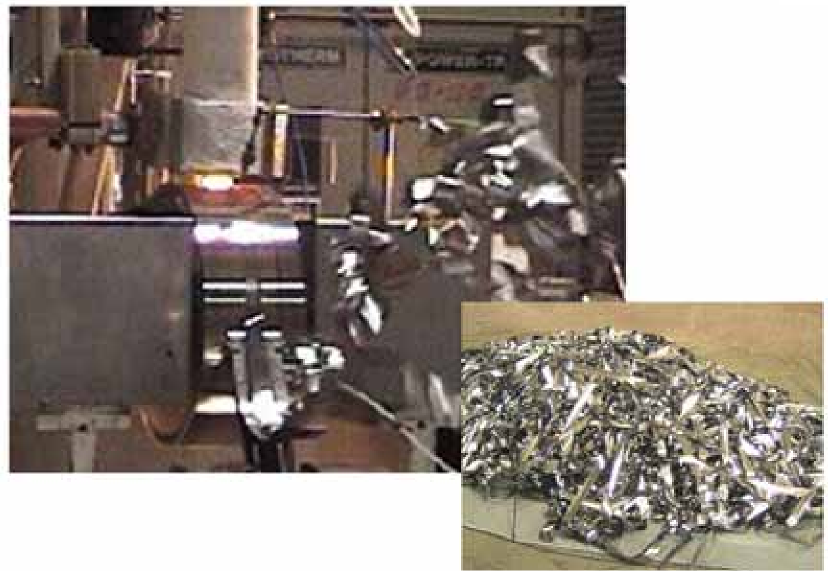


Systems-Level Issues, Passives, and Peripherals Have Not Experienced the Same Level of Sustained Funding Support as WBG Switching Devices.

Major Opportunities and Needs for New Materials Innovations!

Rapid Solidification and Processing of Materials and Cores

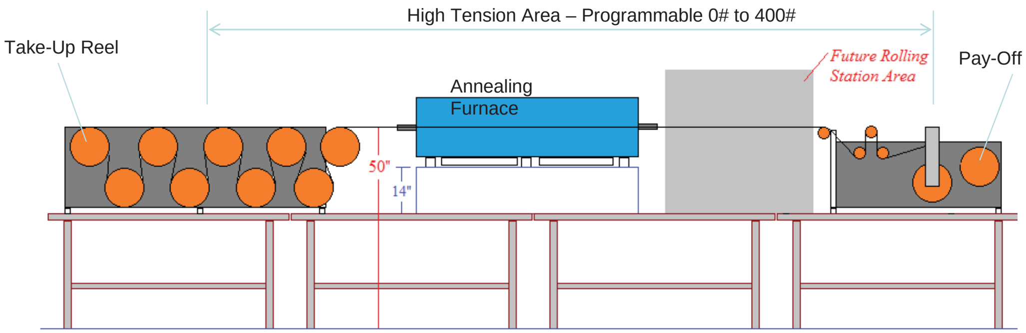
Rapid Solidification Processing Enables Synthesis of Large-Scale Advanced Soft Magnetic Alloys to Enable High Power Device Fabrication



NETL, Carnegie Mellon University, and Nearby NASA Glenn Research Center Collectively Have Close Collaborations and Unique Expertise and Facilities for <u>Alloy Development and Processing, Large-Scale Casting, and Core Fabrication</u>.

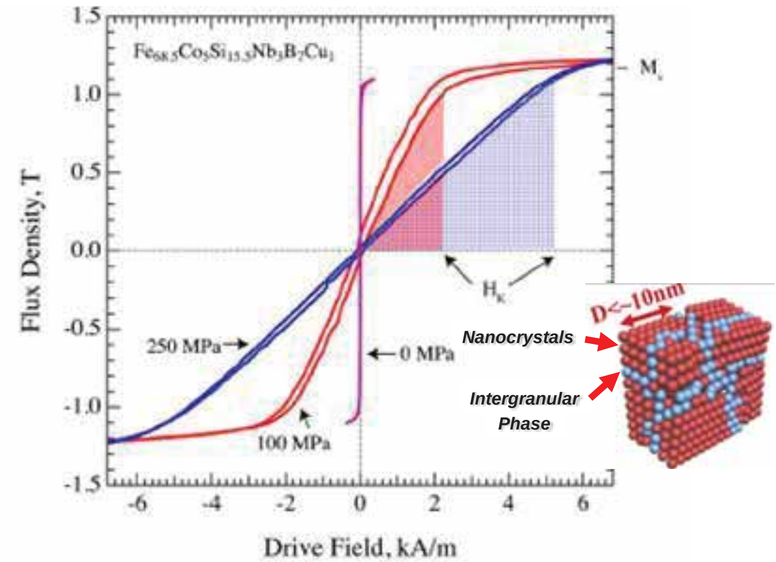
Processing of Alloys to Optimize Permeability / Losses

Commercial Scale Processing / Core Fabrication Facilities



Alloy / Ribbon Processing

- **Thermal**
- **Thermal + Magnetic**
- **Thermal + Mechanical**
- **e.g. Field or Stress Annealing**

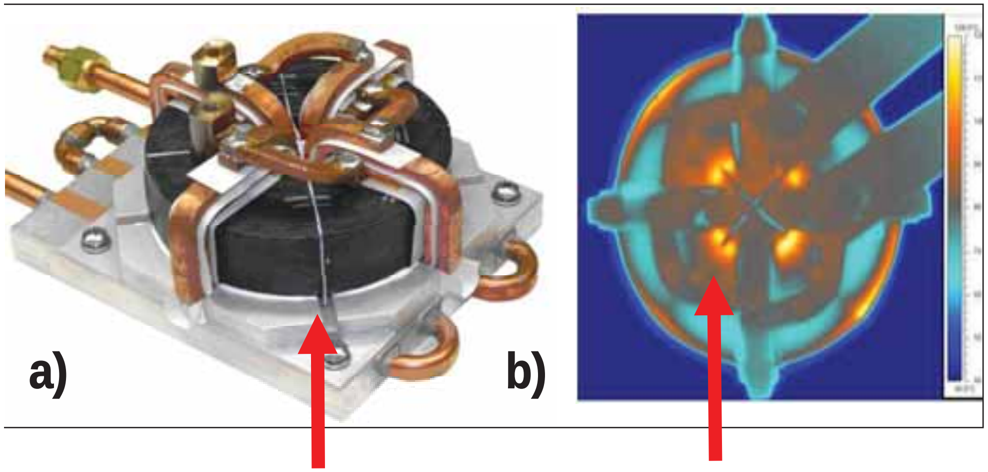


In Addition to Alloy Composition Design, Thermal Processing to Optimize Microstructure and Properties is Crucial and an Area of Major Emphasis.

"Tunable Permeabilities" of Alloy Compositions for a Particular Targeted Level Allows for Core and Alloy Optimization While Mitigating Against Parasitics, Stray Fields, and Fringing Fluxes at the Systems Level.

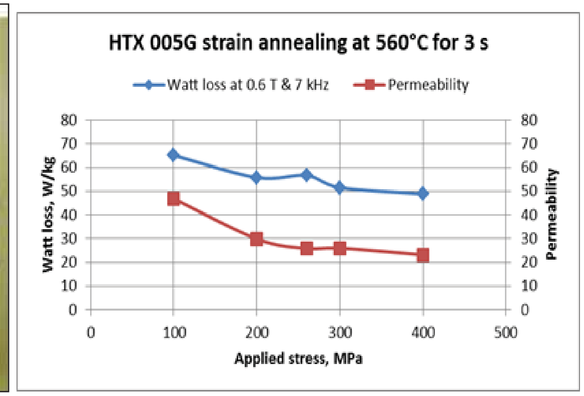
Tunable Permeability Application : Ungapped Cores

CMU / NETL Joint Patent Filed on Strain Annealed Inductor Cores



Core Cutting and "Gapping" or Fabrication of a "Powder Core" to Make a Device Introduces Losses

Tunable Permeability by Strain Annealing Allows for Gap Elimination



Strain Annealing Can Avoid this Processing Step and Eliminate "Fringing Fluxes" / Parasitics

Patent Application Filed

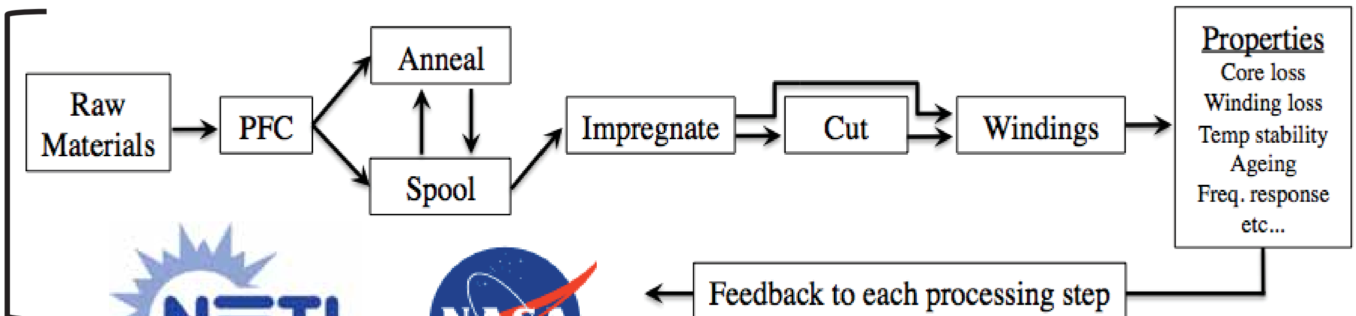
A Combination of Advanced Processing, Novel Alloy Compositions, and Core Fabrication Can Enable Completely New Solutions From the Perspective of Converter and Component Designs.

Vertical Integration of Material, Core, Converter Development

In-Line Ribbon Processing | **Large Number of Alloy Compositions "On-Hand"** | **Broad Array of Final Properties are Attainable**

Alloy	Remarks	Bm, T	µ	P0.2/20, W/kg	Tmax, °C
HTX 002	Nanocrystalline	1.55	1500	4-6	250
HTX 005C	Amorphous	1.02	670	5	
	Nanocrystalline	0.96	480	8	400
HTX 005F	Nanocrystalline	0.89	220	6-8	
HTX 007A	Amorphous	1.52	1k to 3k*	3-5	
HTX 003D	Nanocrystalline	1.20	9k to 18k*	1.5	
2605SA1	Amorphous	1.56	1k to 5k*	10	155
HTX012B	Nanocrystalline	1.25	15k to 20k*	2	125

Core Fabrication and Testing, Process Flow Diagram



Carnegie Mellon University

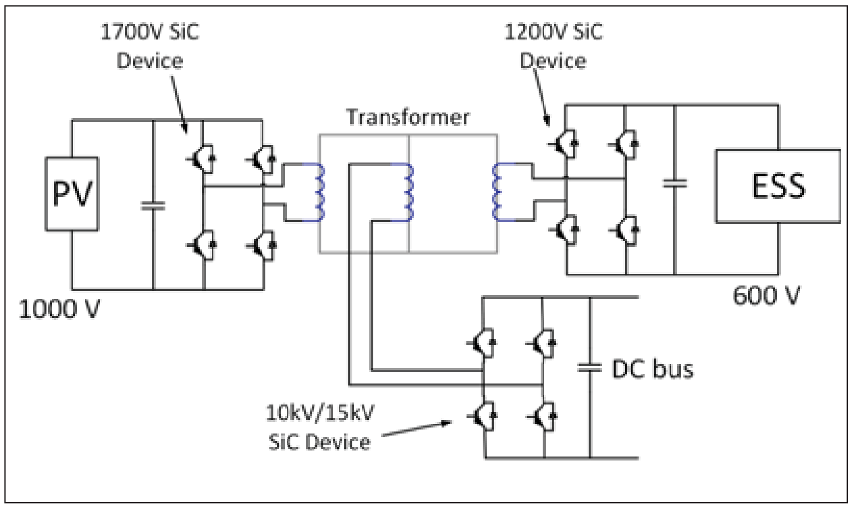
NETL

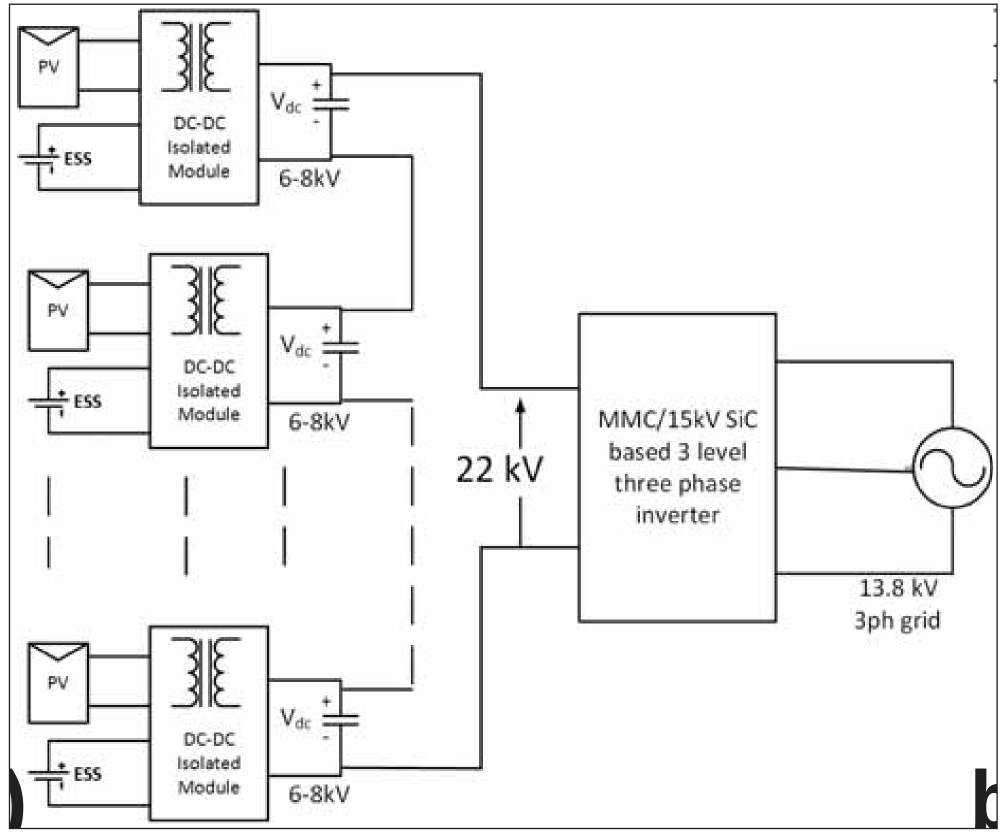
NASA

Integrated Materials Development and Core Fabrication / Processing Activities Should Be Coupled with Converter Design and Development Activities to Ensure the Team Arrives at a "Global" Rather than a "Local Optimization".

(Core Losses, Thermal Management, Parasitics, Inductance, Permeability)

WBG Power Conversion Centered on HF Magnetics





Integration of Solar PV and Energy Storage Into an "Integrated Converter Module" Using a 3-Limb <u>High Frequency Transformer</u> and SiC Switching Devices Grid-Tied Through a DC Bus and a High Power Inverter.

High Frequency Transformers are Also a Foundational Technology for DC-DC and DC-AC Converters Utilized in Power Flow Control, Motor Drives, HVDC, etc.

Advanced Transformer Design to Enable WBG PE Systems

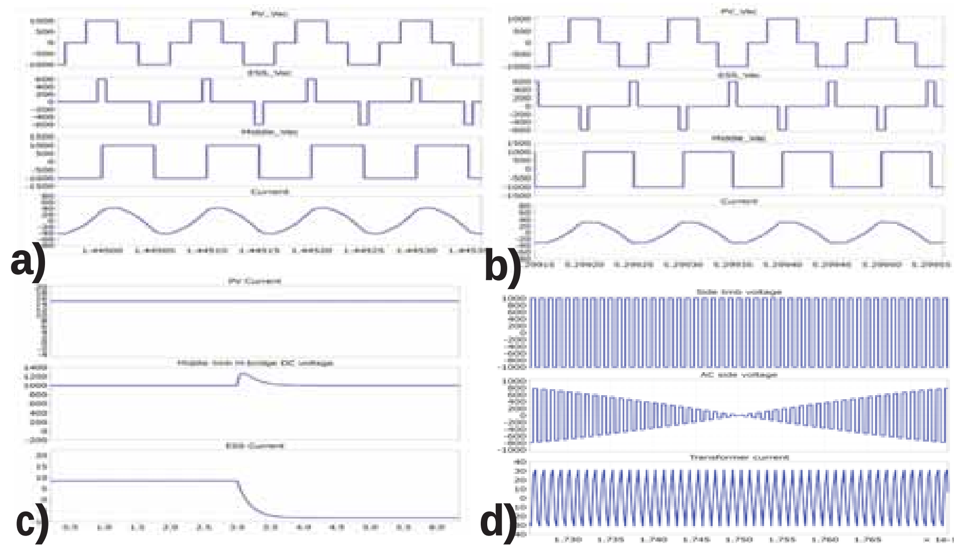
Advances in the High Frequency Magnetics are Critical for Enabling the Integrated Converter Module Approach.

Alloy + Core Advances Required

- Losses, Thermal Management, Parasitics

3-Limb High Frequency Transformer

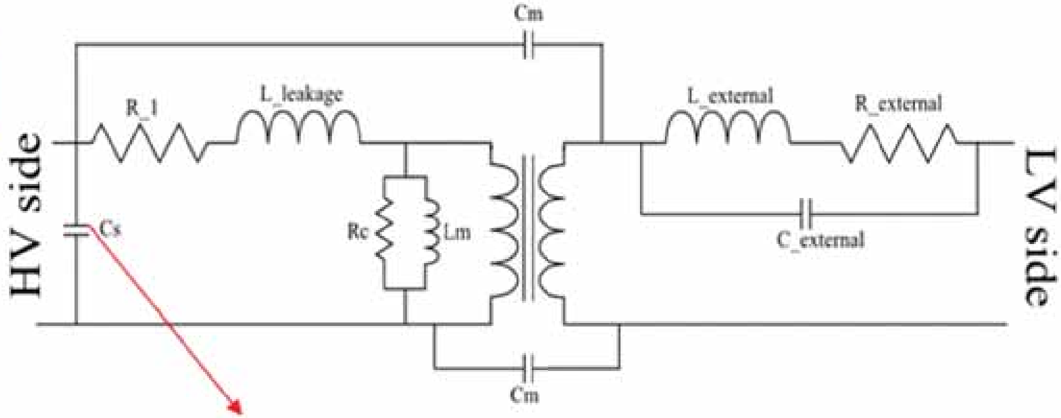
Leakage Inductance	1.2mH
Magnetizing Inductance	15mH
Self Capacitance	50nF
Inter-Winding Capacitance	100pF



Advanced Transformer Design and Winding Principles are Coupled with Alloy Composition and Processing Research, Core Fabrication, and SiC Power Electronics Converter Designs to Address System Level Needs.

Realistic Models of High Frequency Transformers

High frequency Transformer Parameter Value[Units]	35kVA,22kV/800V Measured parameters	1MVA,16kV/2kV Scaled parameters
Total Equivalent self parastic Capacitance,Cp	50pF	52pF
Total Mutual Capacitance ,Cm	1200pF	208pF
Mag. Inductance, Lm	293mH	640mH
Total Leakage from HV side	643µH	0.37mH
Equivalent core loss resitsance(Rc)	6MΩ	1MΩ



Transformer parasitic parameters	
Self capacitance	52pF
Mutual capacitance	208pF

- The parasitic capacitances cause spike current in the device which decides the current de-rating of the device
- The High speed SiC devices may cause high dv/dt across the transformer and hence spike current through the parasitic capacitances

Parameters	15kV SIC IGBT device data	10kV SIC MOSFET device data	6.5kV SI IGBT device data
Rise time	500ns	197ns	350ns
falltime	1us	144ns	3.8us
device capacitance	0.01nF	0.01nF	0.001nF
stray inductance	5.4nH	5.4nH	5.4nH

Parameters	JBS diode (SiC) device data	Si -diode device data
reverse recovery	350ns	3.4us
Qrr	0.79uC	370uC
stray inductance	5.4nH	5.4nH

Parasitics Must Be Addressed for Successful Application of HF Transformers. Geometry, Windings, Insulation, Core Material and Processing All Play a Role Requiring an Interdisciplinary Team.

Courtesy of Prof. Subhashish Bhattacharya, NCSU

Summary and Conclusions

Key Message #1:

- WBG Switching Devices are Beginning to Reach Maturity and Commercialization Due in Part to Long-Term Sustained Government Investment
- Systems Level Issues Will Increasingly Limit Widespread Deployment
  - Parasitics, Harmonics, and EMI
  - Thermal Management
  - Passive Components (HF Magnetics, HT Capacitors)
- Materials R&D Can Significantly Impact Systems-Level Concerns Just as it Has for the WBG Switching Devices
- No Program in DOE Currently Provides Sustaining R&D Support Focused Primarily on Passives and Other Systems Level Issues at T&D Scale for WBG Power Electronics

Key Message #2:

- A Need Exists for Sustained DOE Support in Soft Magnetic Material Development, Manufacturing, and Device Integration (Transformers, Inductors, Motors)
- No US-Based / US Owned "CREE" of Soft Magnetic Alloys Exists Requiring Teaming Arrangements to Produce "Vertical Integration" for Optimized Materials R&D
- Coupled Magnetic Materials and Device Development is Needed for Enabling HF and HV WBG Power Electronics Converters and Topologies
- High Frequency Transformers / Filter Inductors are at the "Core" of Renewable Integration, Power Flow Controllers, HVDC Converters, Solid State Transformers, etc.

Thank You to ORNL and DOE OE for the Opportunity to Attend and Present!

Please Contact Me if Interested in Discussing Potential Collaborations, Technical Support to Program Planning, or Further Details Regarding this Presentation.

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