Advanced SiC Power Module Packaging : Layout, Material System and Integration

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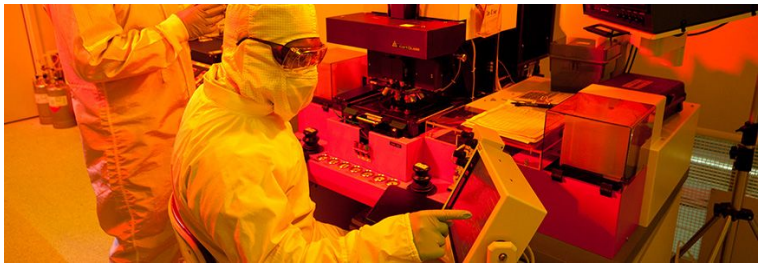
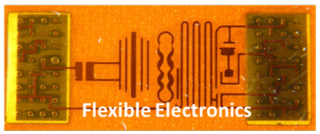
UA Packaging Program

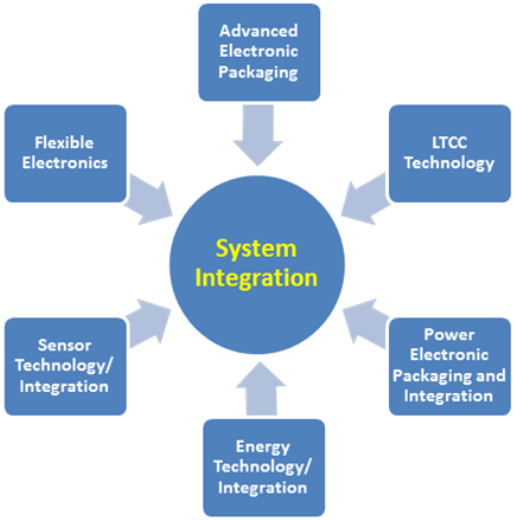
Advanced Power Module Packaging for WBG Devices



High Density Electronics Center (HiDEC)

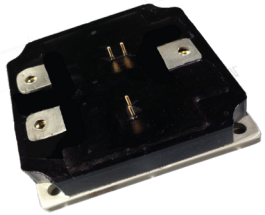


Flexible Substrate Solutions



HiDEC Scope

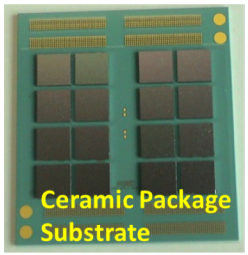
TO247

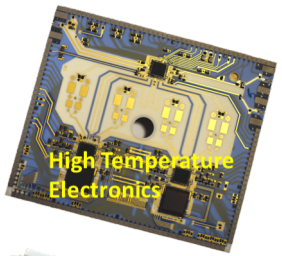


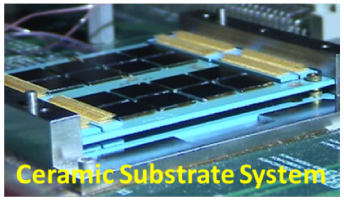
Custom High-Temperature Power Module

Standard 62-mm Module

Power Module Packaging







Ceramic Packaging Solutions

MV Testing facility:

National Center for Reliable Electric Power Transmission (NCREPT)

Three R&D 100 Awards: 2009, 2014 and 2016

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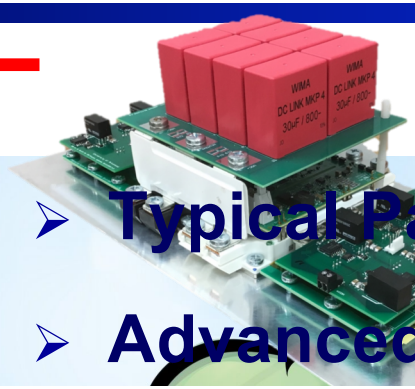
Outline



EMI, PD and RFW

- Typical Packaging Material System
- Advanced Module Layouts

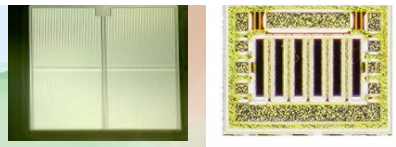
Converter Level Packaging and System

- Improved Wirebonded Structures & EMI-Less Module

Side-Effect Mitigation in WBG converters

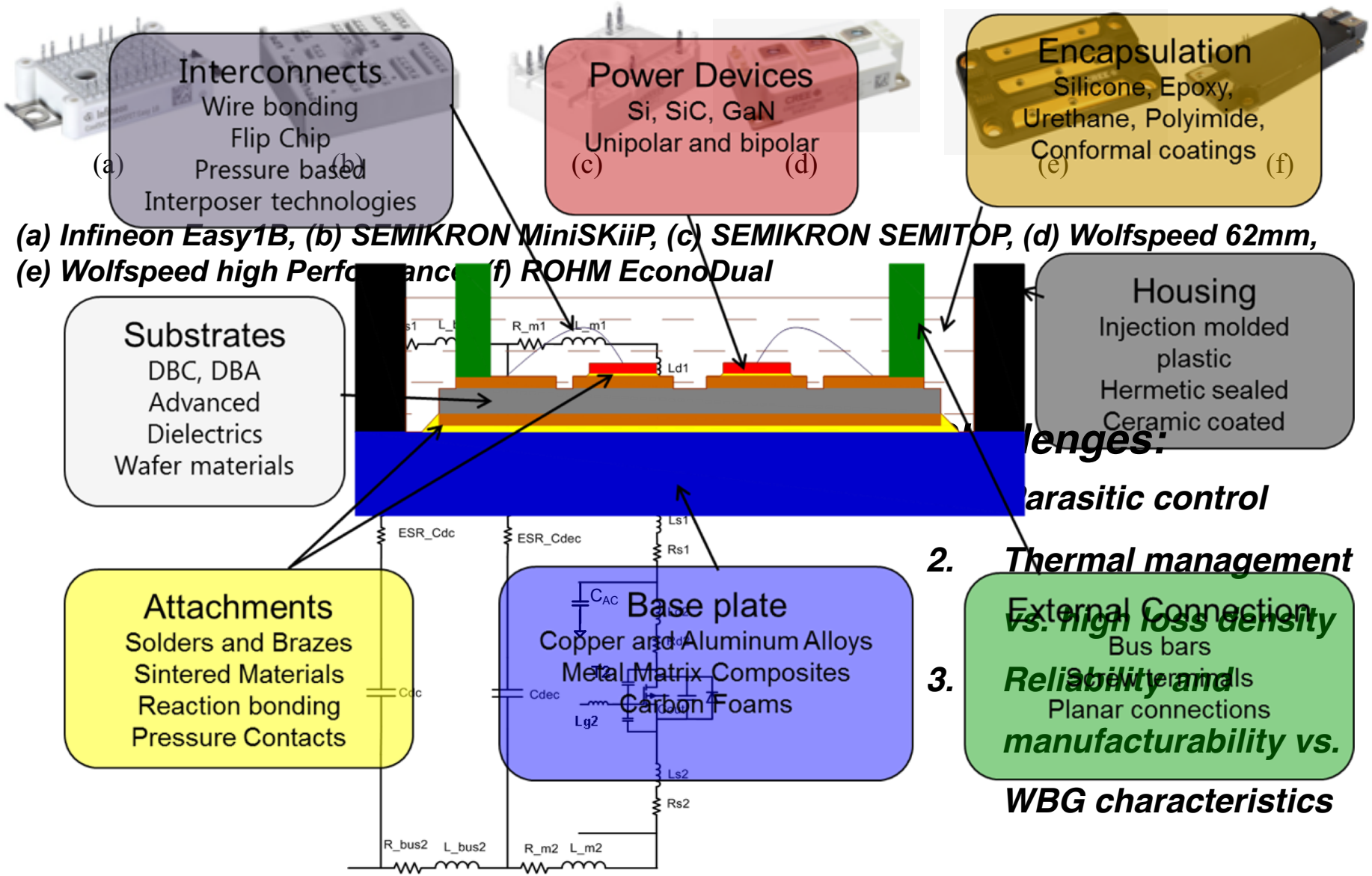
- Wireless Structures
- High Voltage Modules
- Busbar Vs. Power Module – Tradeoff at PEBB Level
- Power module co-design

Power Module Packaging



WBG Devices

State-of-the-Art and Limitations



(a) Infineon Easy1B, (b) SEMIKRON MiniSKiiP, (c) SEMIKRON SEMITOP, (d) Wolfspeed 62mm, (e) Wolfspeed high Perfo[illegible]ance, (f) ROHM EconoDual

[illegible]lenges:

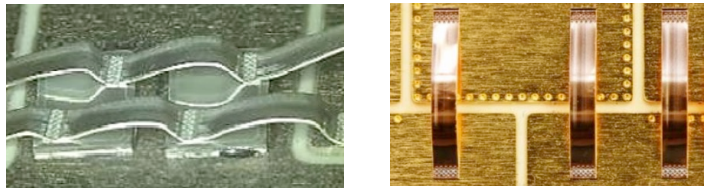
[illegible]arasitic control

2. Thermal management vs. high loss density

3. Reliability and manufacturability vs. WBG characteristics

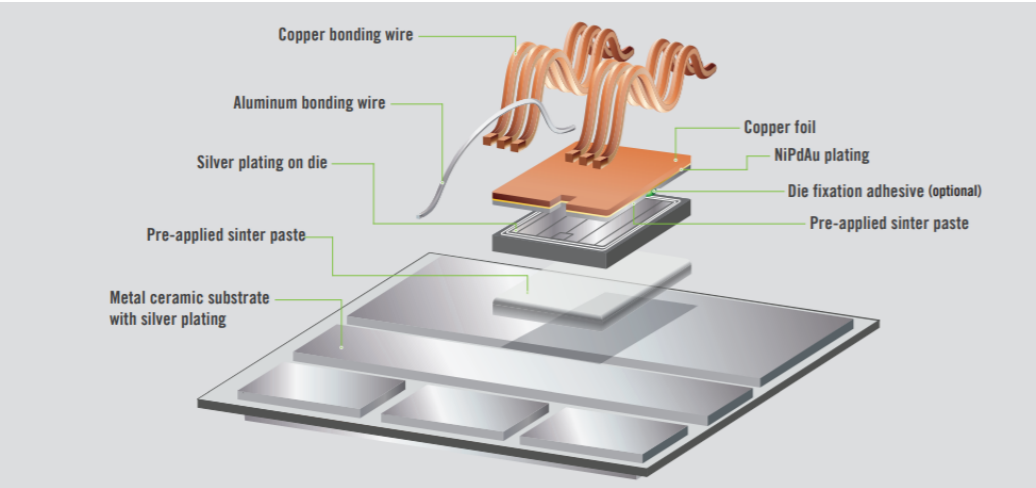
Power Module Interconnections

	Stray Inductance	Current Capacity	Power Cycling	Double side cooling	EM Loop
Wire-bond	High	Low	Low	N	High
Ribbon Bond	Medium	High	Medium	N	Medium
Wireless bonding	Low	High	Case-by-Case	Y	Low



(a) (b)

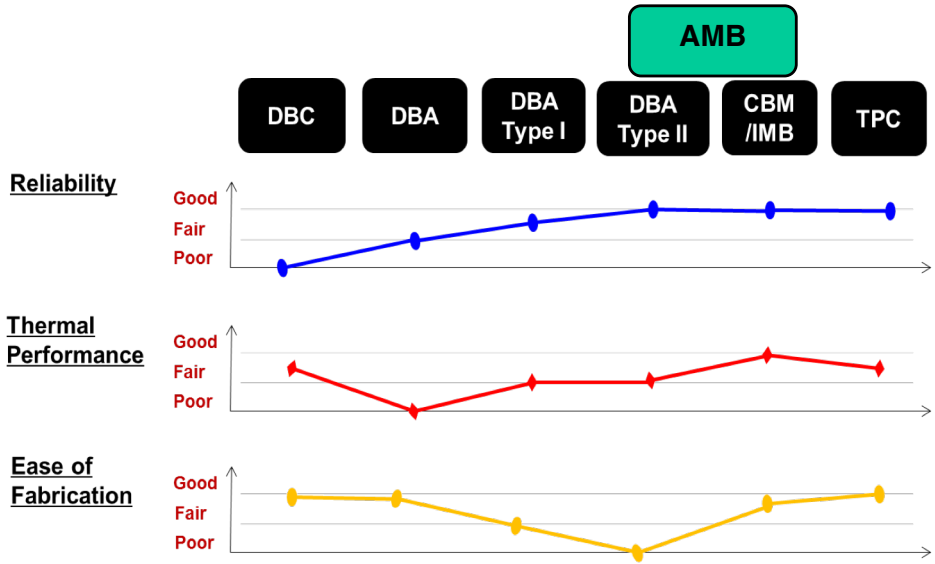
Ribbon Bonding

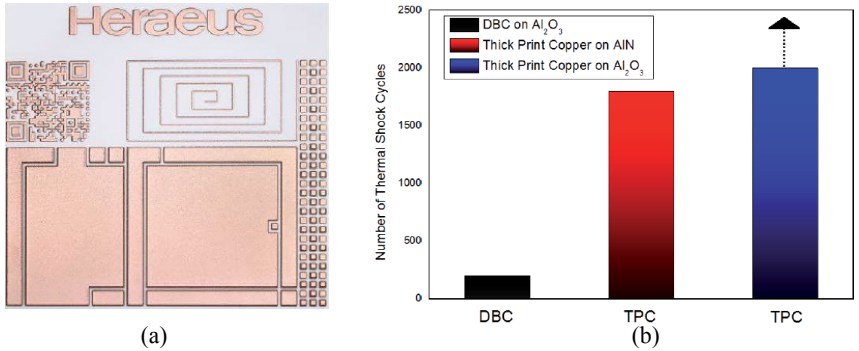


Heraeus Die Top System

Substrates

	Si_3N_4	AlN	Al_2O_3	BeO
Dielectric constant	8~9	8~9	9~10	6-8
Loss factor	2×10^{-4}	3×10^{-4}	3×10^{-4}-1×10^{-3}	3×10^{-4}
Resistivity (Ω·m)	> 10^{12}	> 10^{12}	> 10^{12}	> 10^{12}
Dielectric breakdown strength (kV/mm)	10 - 25	14 - 35	10 - 35	27-31
Thermal conductivity (W/m·K)	40-90	120-180	20-30	209-330
Bending strength (MPa)	600-900	250-350	300-380	≥250
Young Module (GPa)	200-300	300-320	300-370	330-400
Fracture toughness (MPa·$m^{1/2}$)	4-7	2-3	3-5	1-2.5
CTE (mm/m·K)	2.7-4.5	4.2-7	7-9	7-8.5
Available substrate technologies for thick film metallization	AMB	DBC/DBA AMB	DBC/DBA	DBC





TPC substrate: (a) 300μm thick printed copper substrate, (b) reliability comparison results.

CBM: Ceramic Bonded Metal

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Die Attachment

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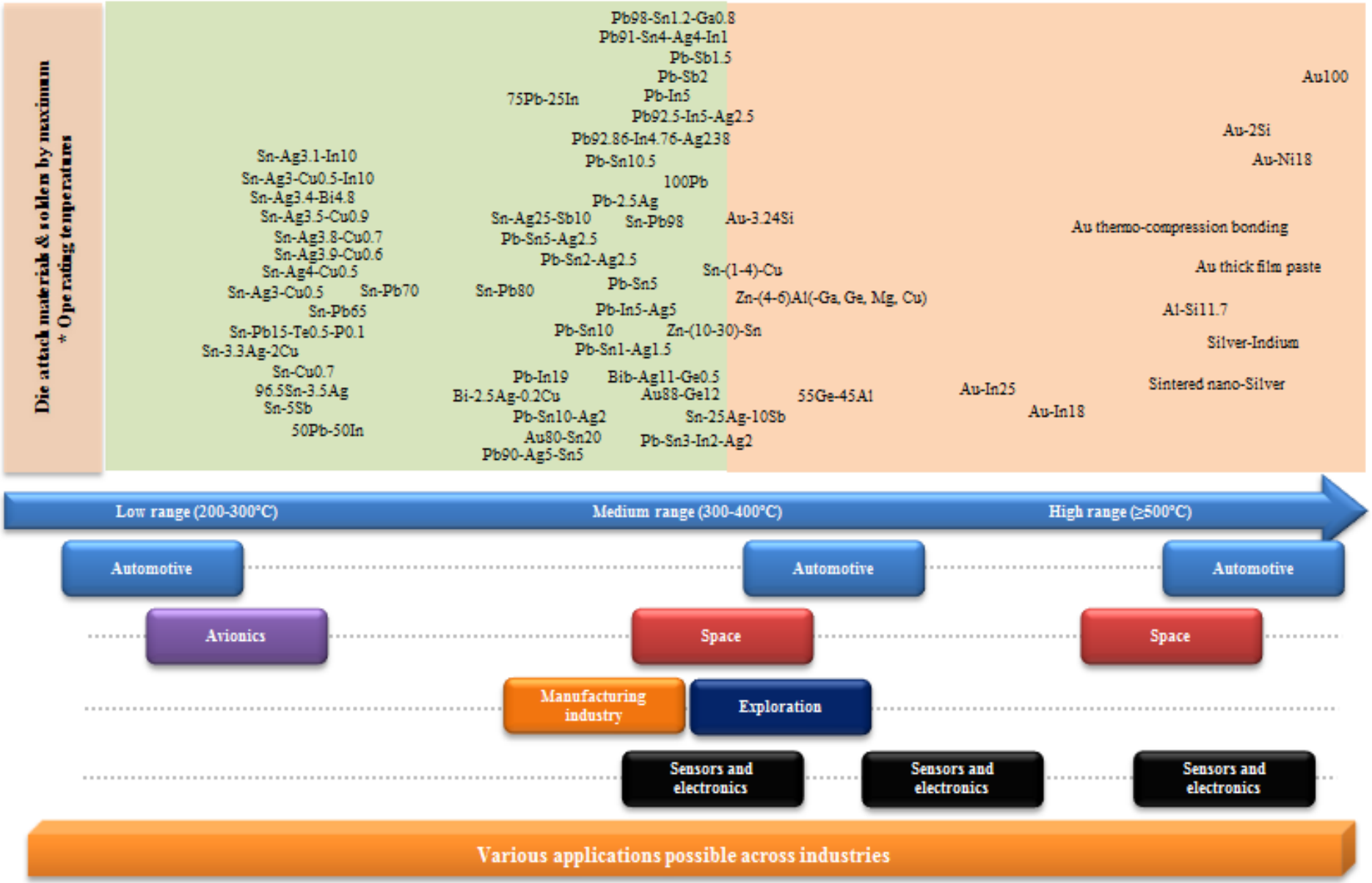
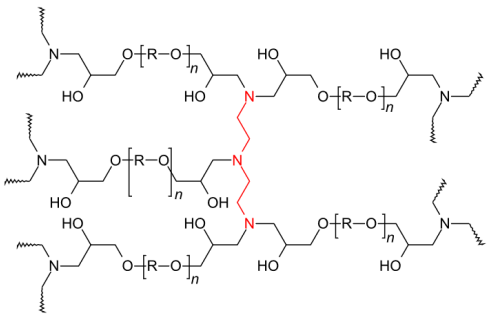
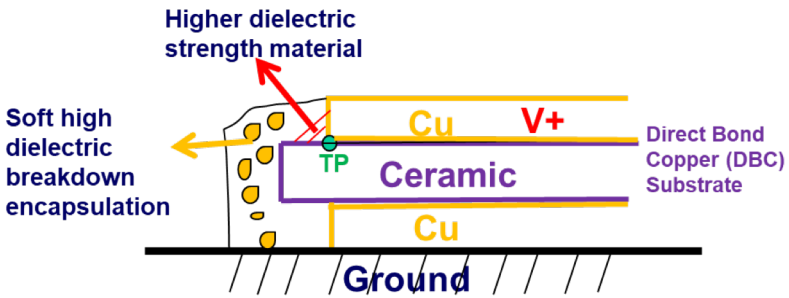


Encapsulation Material

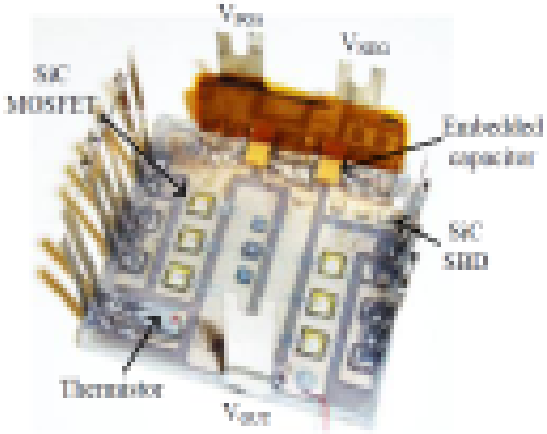
Material	Part Number	Manufacturer	Dielectric Constant	Breakdown strength	Temperature Range (ºC)
Dielectric Fluid	Novec® 7500	3M	5.8	35 kV, 0.1" gap	128 max.
Polyamide Imide (PAI)	Torlon® 4203	Boedeker Plastics	4.2 (@ 1 MHz)	100 – 280 kV/mm	260 max.
Epoxy	Hysol® -60NC	Henkel	21.7	20 kV/mm	-
Silicone	3-6635	Dow Corning	20.5	20 kV/mm	-80 to 200
Silicone	Sylgard® 567	Dow Corning	2.79 (@ 100 kHz)	16 kV/mm	-45 to 200
Silicone	TSE3051	Momentive	2.8	18 kV/mm	-
Silicone	CF2186	Nusil	35.4	19.5 kV/ mm	-140 to 315
Silicone	R-2188	Nusil	2.6 (@ 100 kHz)	19.5 kV/mm	-
Benzocyclobutene (BCB)		Dow Chemicals	2.65	530 kV/mm	
Poly (dimethyl diphenyl) siloxane Gel	RTX-5	Restek	2.8 (@ 1 kHz)	200 kV/cm	265 max.



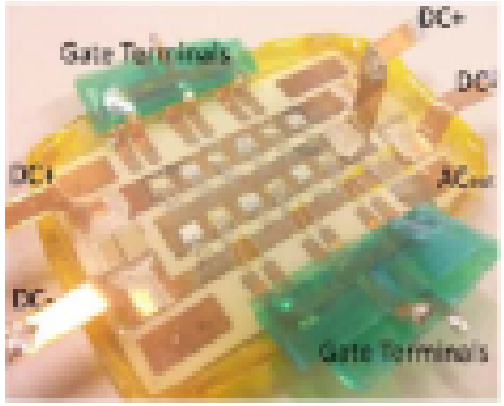


Nano-Ceramic Enhanced Encapsulation, S. Ang, UArk

Improved Wire-bonded Structure



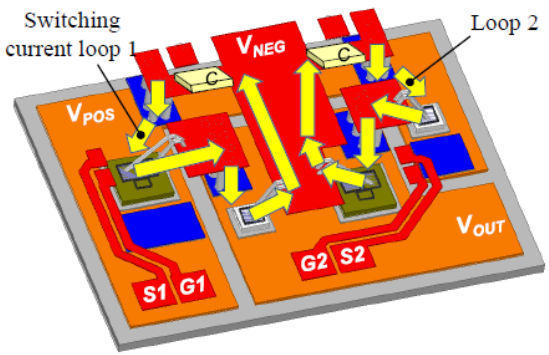
HT SiC Module, Z. Chen, CPES 2012



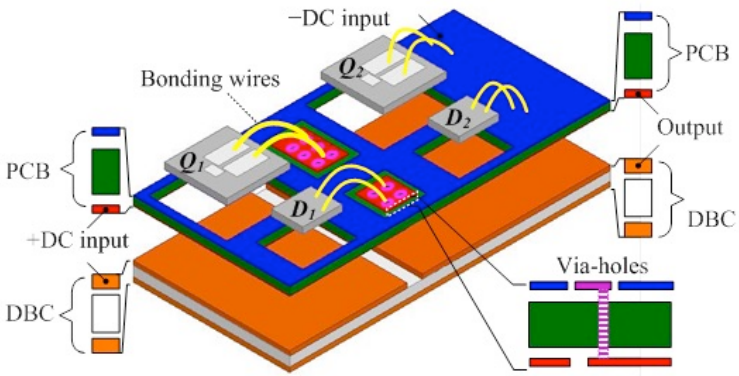
Double Ended Sourced SiC Module, M. Wang/F. Luo, OSU/Uark 2017

Highlights:

1. ***Relatively mature processes and material systems***
2. ***Reduced Bond-wires***
3. ***Improved dynamic current sharing in device paralleling***



Hybrid Packaged SiC Module, Z. Chen, CPES 2012



Hybrid Packaged SiC Module, C. Chen / F. Luo, HUST/Uark, 2017

EMI-less Power Module

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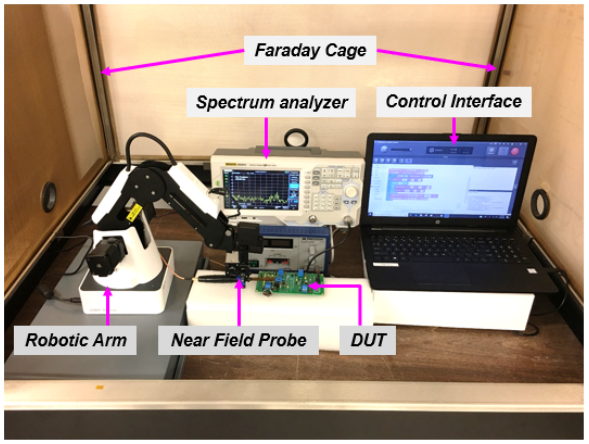
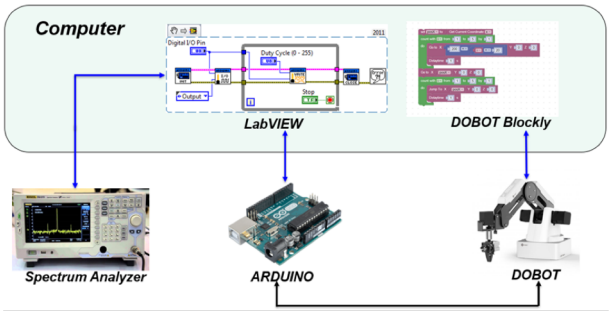


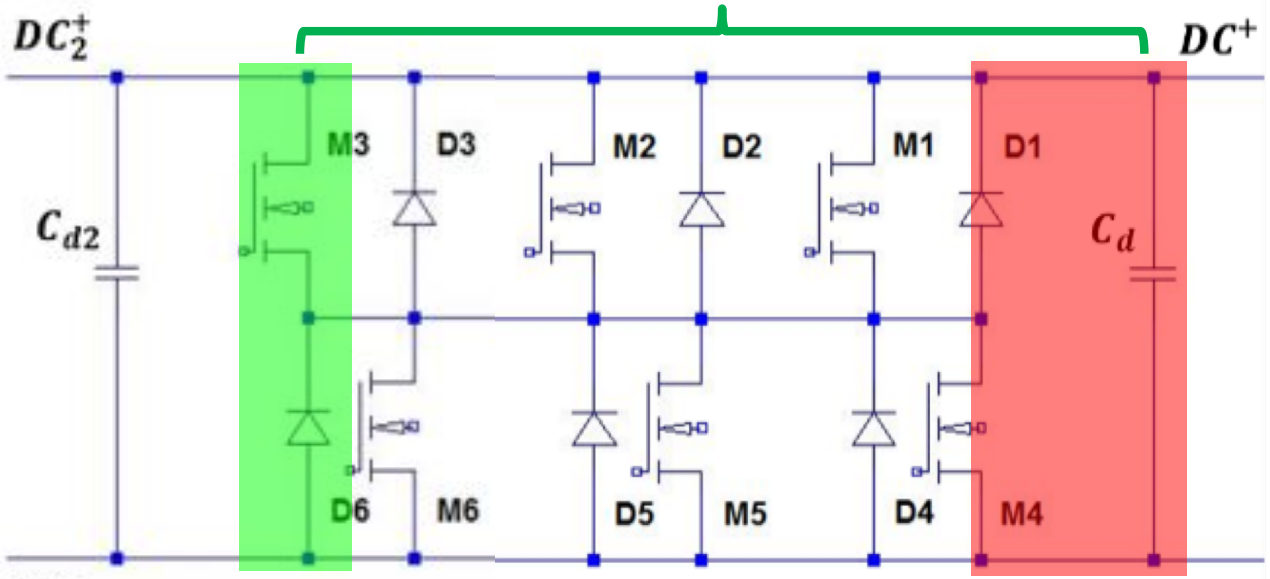


Radiated EMI measurement block

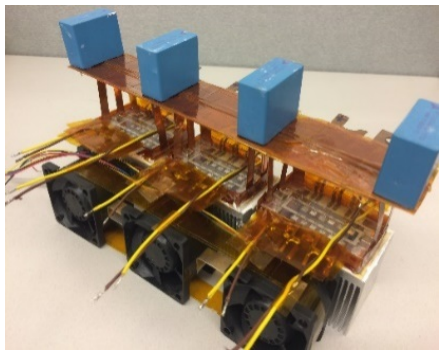
Features

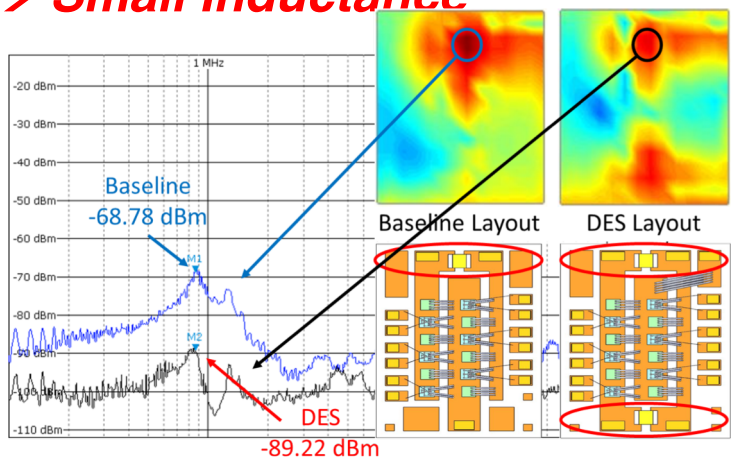
- High repeatability
- High Precision (0.2 mm step size)
- Automatic data acquisition
- Post processing capability

Long Distance → Large Inductance



Short Distance → Small Inductance





EMI-Less Power Module Design

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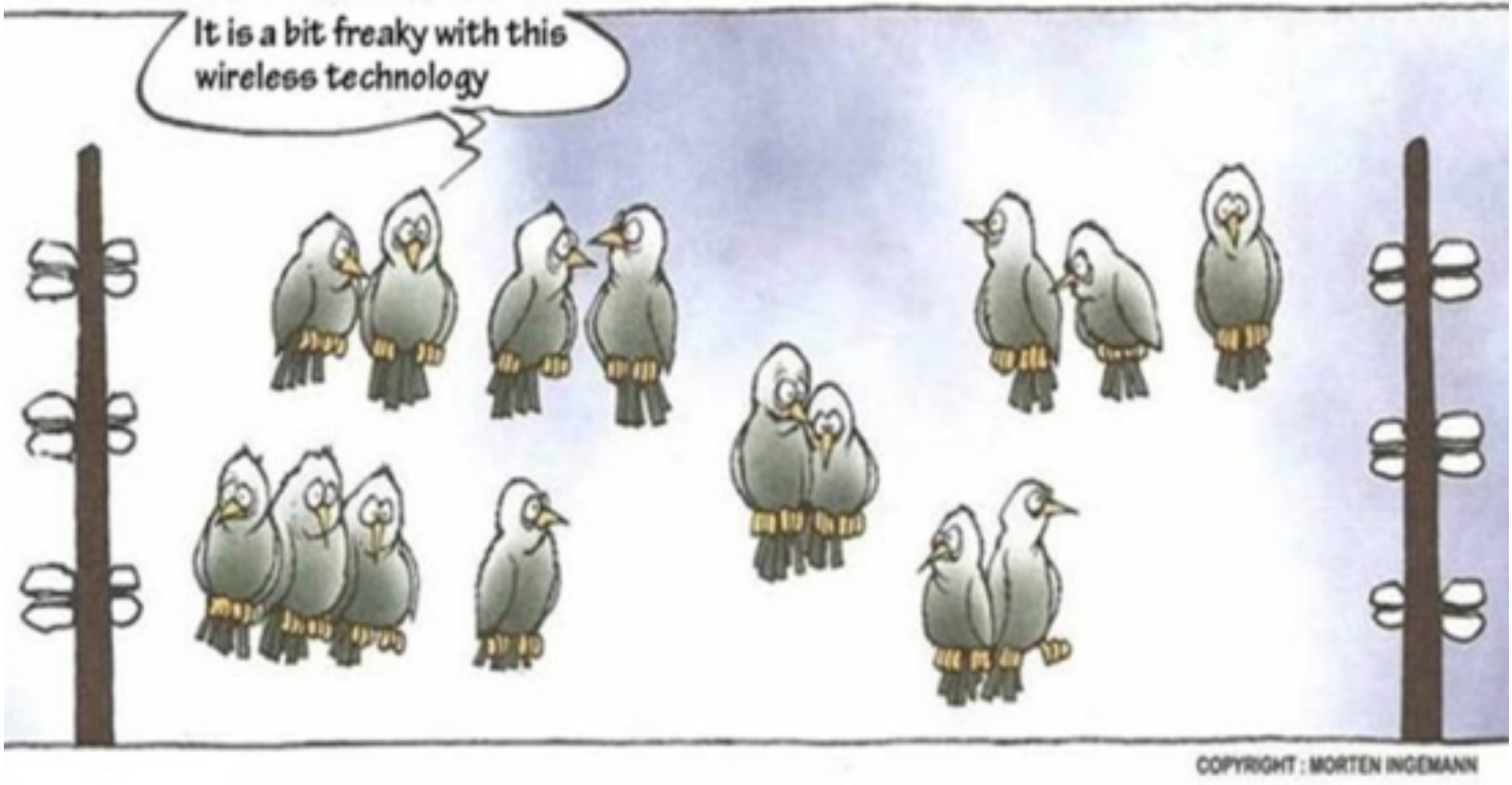
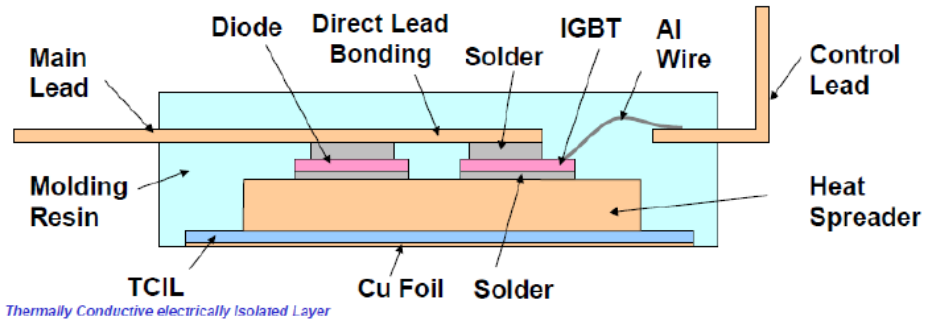
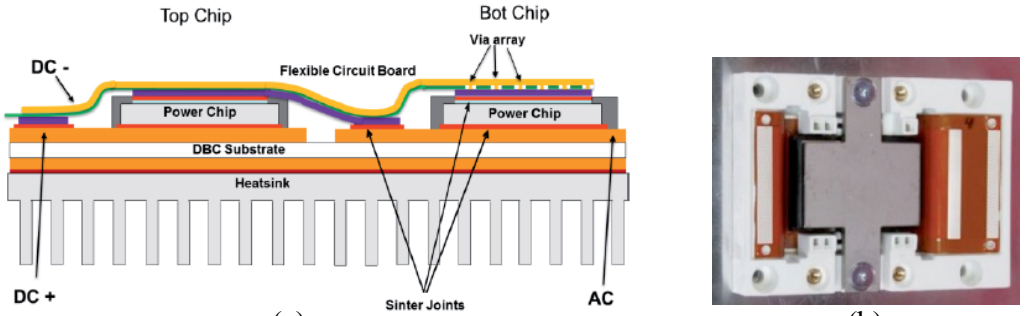

It is a bit freaky with this wireless technology
COPYRIGHT : MORTEN INGEMANN

Wire-less Structure (1)

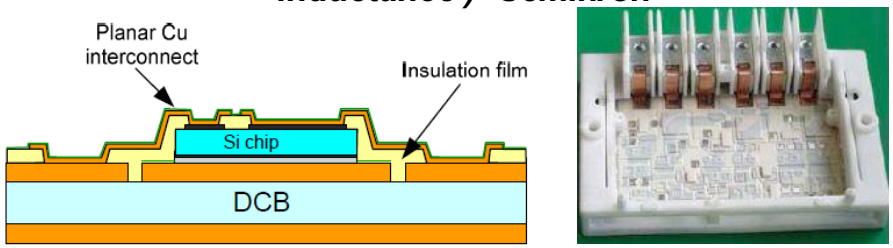


Direct-Lead-Bonding (DLB)



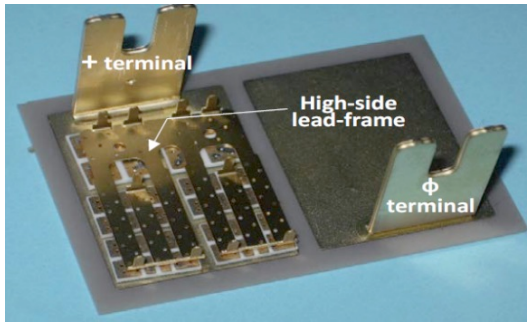
(a) (b)

SKiN technology used in SiC power module: (a) Modified SKiN structure, (b) 1200V/400A power module (1 nH loop inductance)- Semikron



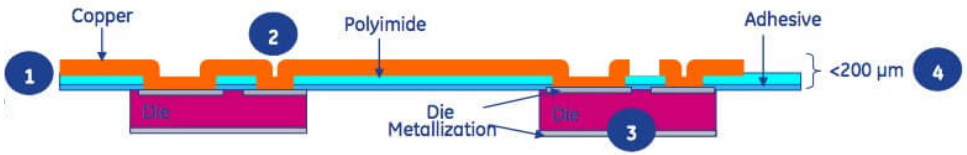
(a) (b)

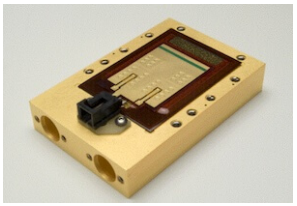
SiPLIT technology: (a) cross-section of power module, (b) SiPLIT module.



Full SiC DLB module by Silicon Power Corporation

STMicroelectronics SiC module for Tesla Model 3





PWB like planar inter-connection

GE Power Overlay (POL)

- ***Significantly reduction of power loop inductance***
- ***Potential for double-side cooling***

Wire-less Structure (2)

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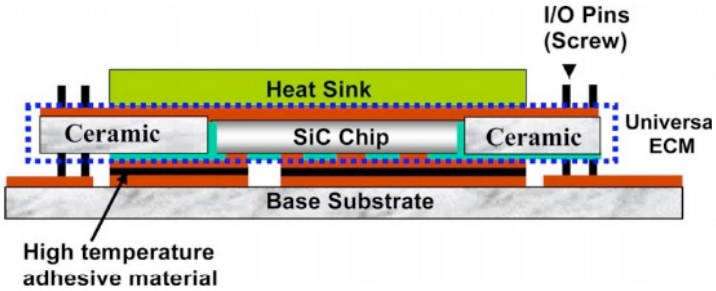
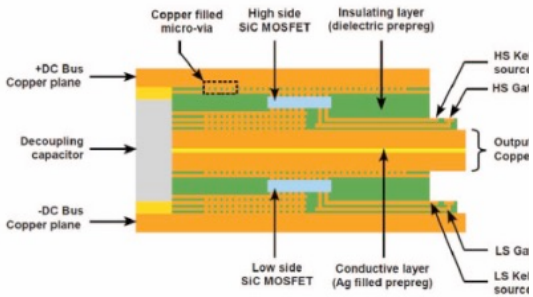
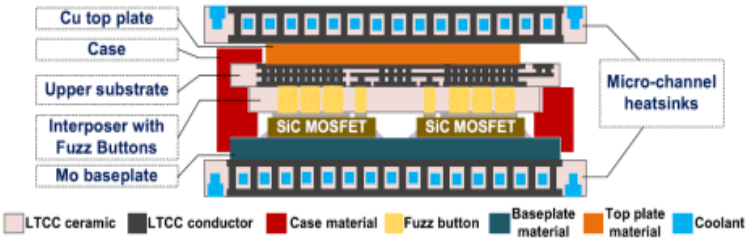


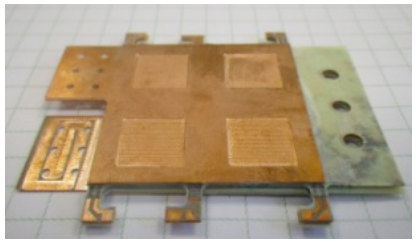
CPES Embedded Power



(a)

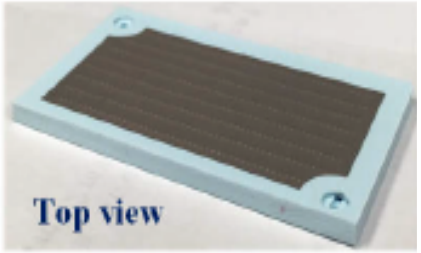


Chip in Polymer (CIP) Embedded Power Package (GaNPX® Package)

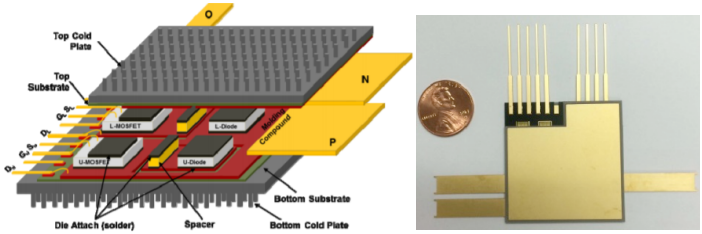


(b)

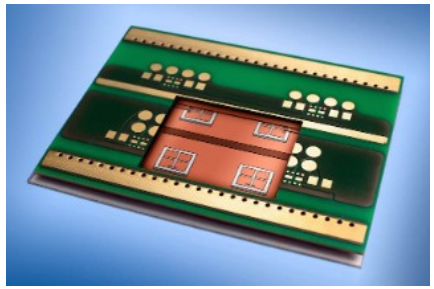
Ampere Lab, Chip-on-Chip (CoC) SiC Module



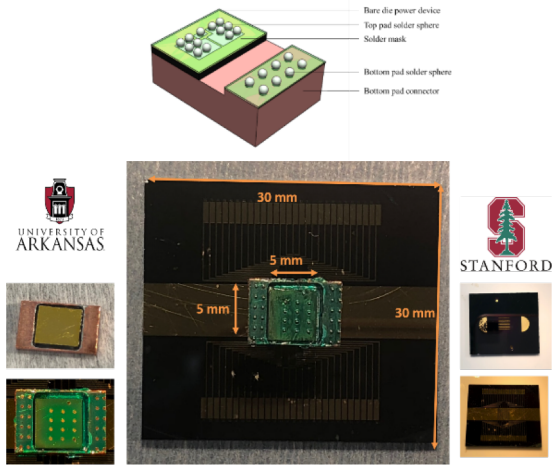
H.Mantooth, UArk PressPak



ORNL Shim-connected Planar SiC Module

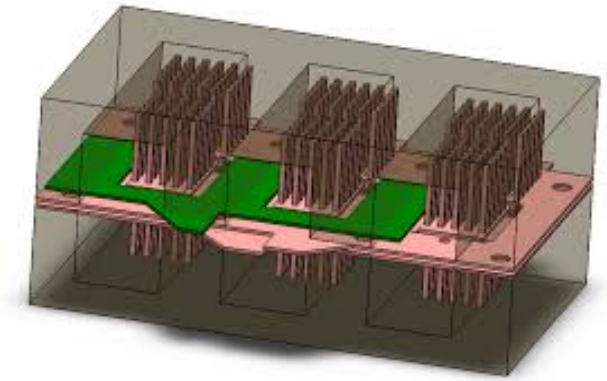


Fraunhofer IZM
90A embedded power module

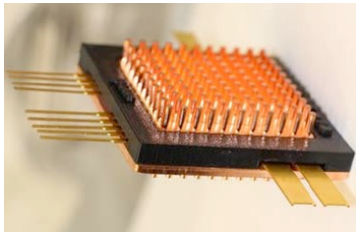


H.Mantooth, UArk BGA FlipChip SiC Package

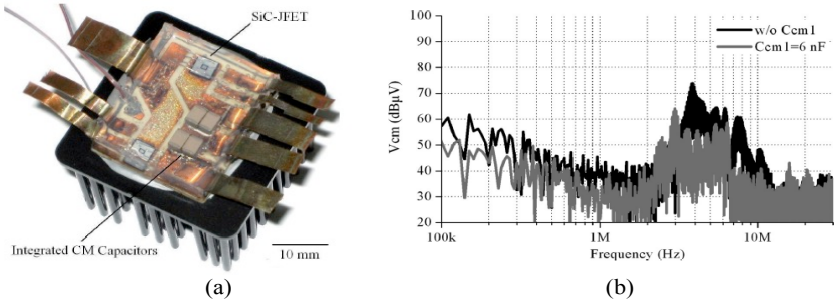
Integrated Modules



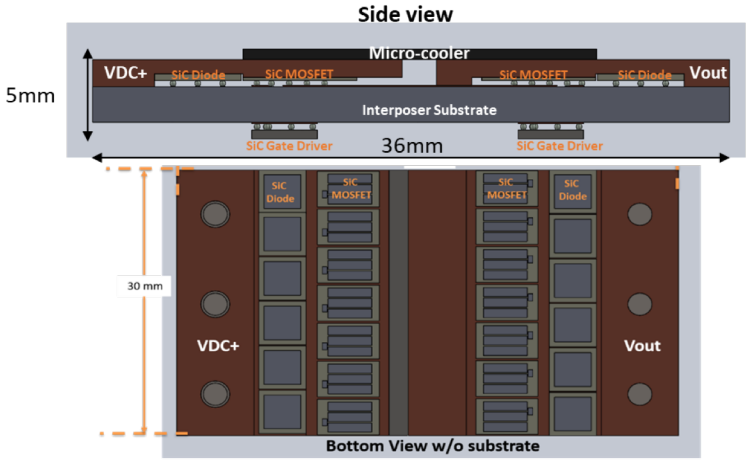
D.C.Hopkins, NCSU, Power Chip on Bus (PCoB) module



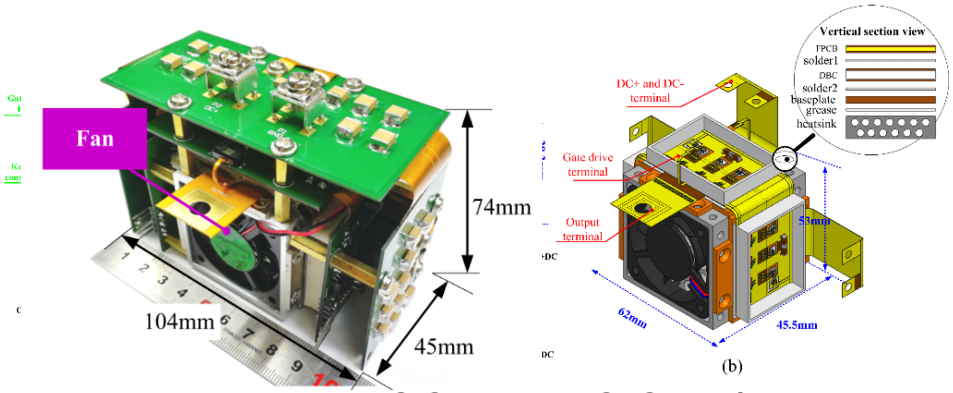
ORNL, Planar SiC module with Pin-fin heatsink



Ampere Lab, HT SiC Module with integrated CM Capacitor



H.Mantooth, UArk BGA FlipChip Integrated SiC Package

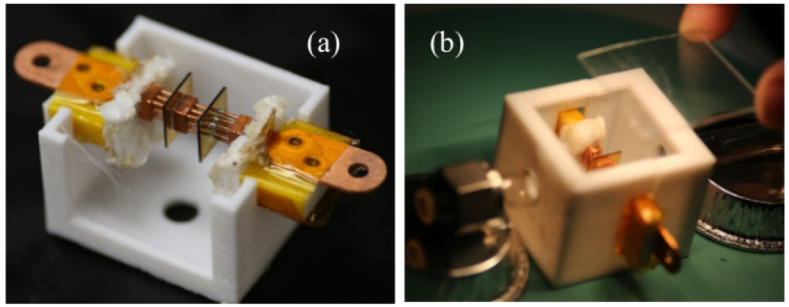


3D Packaged SiC Module, C. Chen / F. Luo, HUST/Uark, 2018

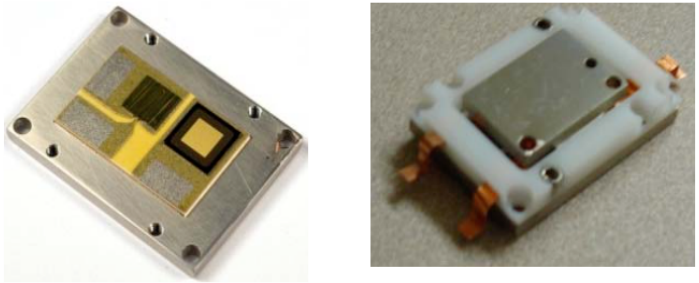
- ***Wafer-level integration is not included here***

High Voltage Packaging Structure

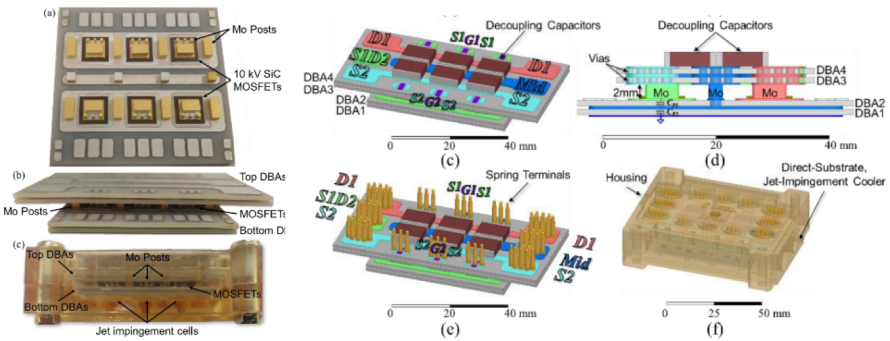
Advanced Power Module Packaging for WBG Devices



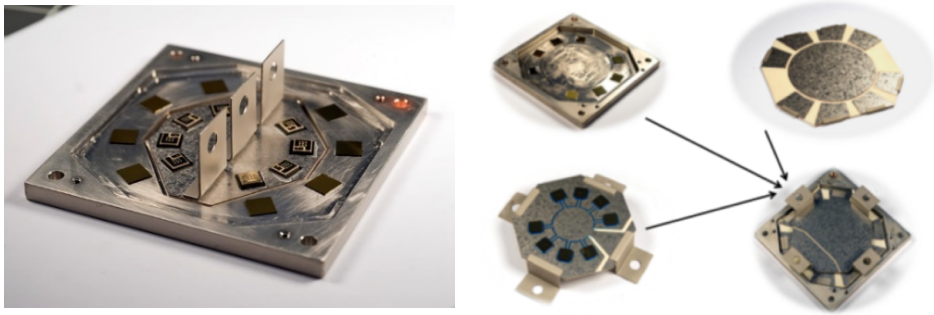
ARL Stacked SiC diode package with integrated thermal management



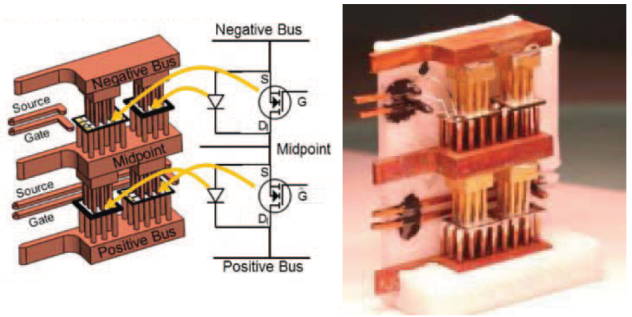
UARK 6.5kV Wire-bondless, Double-sided Cooling Power Electronic Module



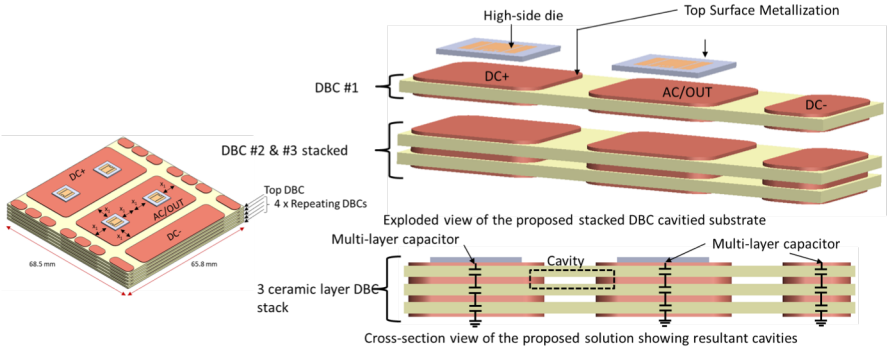
CPES, VT, 10 kV/ 54 A wire-bond-less module



UARK 10 kV SGTO and Diode



ARL Substrate-less design



UARK Stack DBC Design

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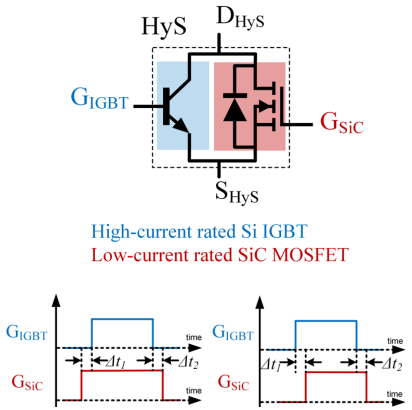
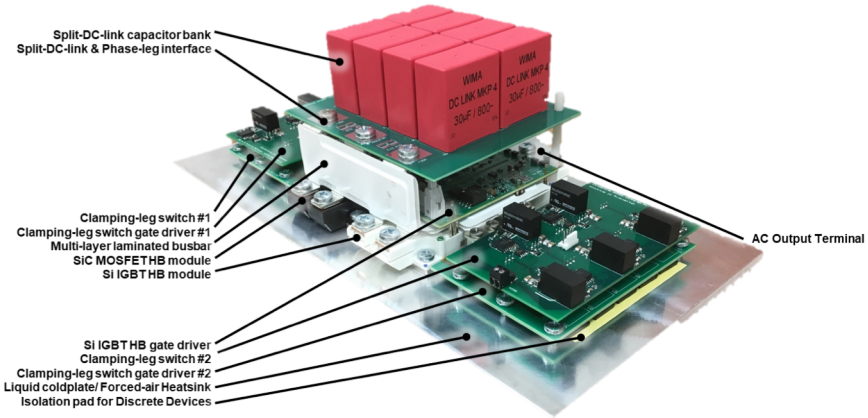
4H PEBBs for Aircraft Propulsion

Advanced Power Module Packaging for WBG Devices





Achievements:

Weight^*: 2.1 kg

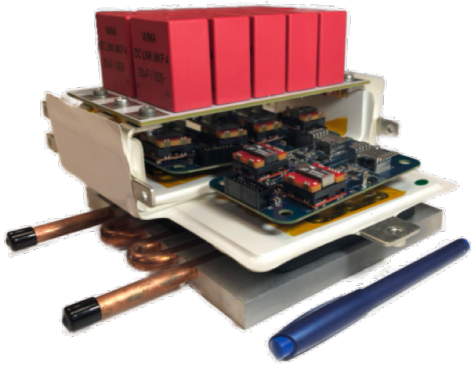
Volume^*: 12" x 6" x 4.5"

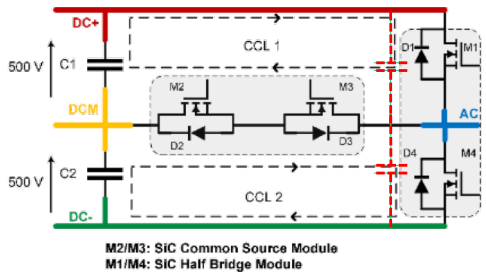
Specific Weight Density #* : 27.7 kW/kg

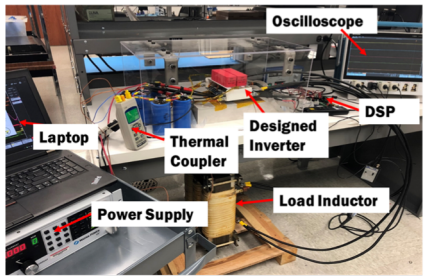
Power Density #* : 308.61 W/in³

**** Excluding EMI Filters & Cold plate***

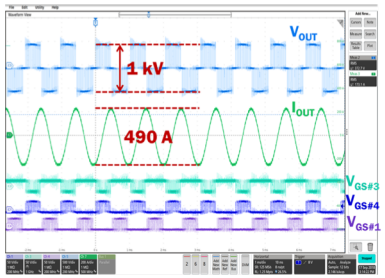
Gen 1: Si IGBT- SiC MOSFET Hybrid 100 kW PEBB (L_{bus} = 15 ~18nH)







Continuous test setup



Captured Waveform

- ***Specific Power = 35.36 kW/kg***
- ***Optimized for less EMI emission***

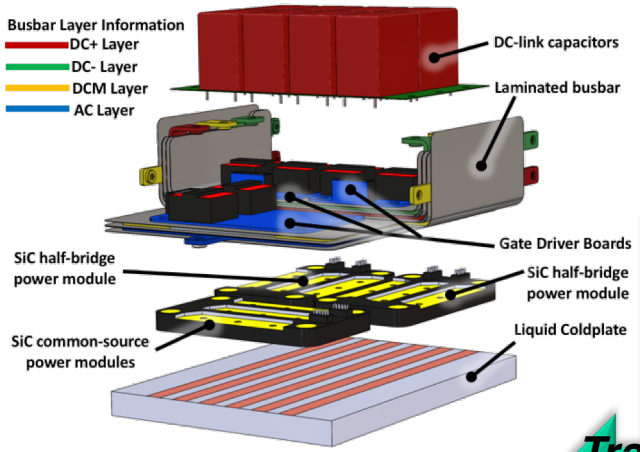
- ***Continuous test at 64.5 kVA, V_{DClink} =1 kV, f_{sw} = 30 kHz***
- ***Measured efficiency of 99.45%***

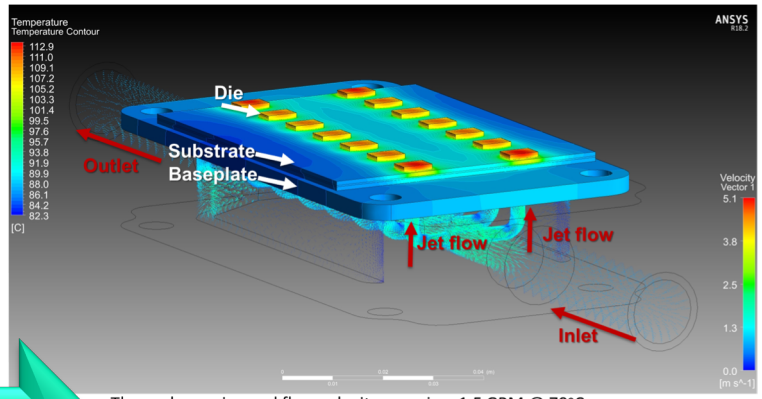
Gen 2: SiC MOSFET 150 kW PEBB (L_{bus} = 11 nH)

"Sandwich" does not always help in WBG converters

Electric-Thermal Co-Design and Optimization

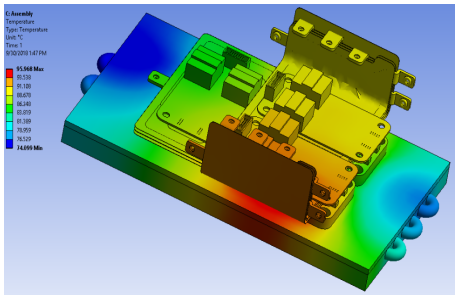
Advanced Power Module Packaging for WBG Devices





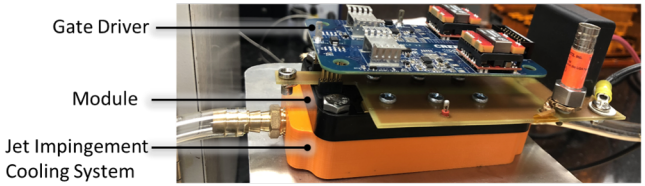
Thermal mapping and flow velocity mapping, 1.5 GPM @ 70°C

Traditional ***Advanced***

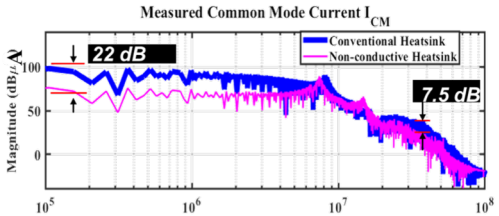


Temperature distribution, 150 kW, 1 GPM @ 70 °C

3D Printed Non-metallic coldplate



Test Setup ($R_{G,ON}$ = 5 Ω, $R_{G,OFF}$ = 2.5 Ω)



- **Optimized Jet-Impingement coldplate**
- **3D Printed with non-metallic material for EMI optimization**
- **Busbar is optimized for thermal/stray inductance/ stray capacitance**

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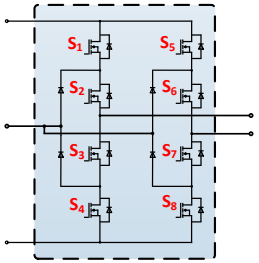
PowerSynth-Design Automation

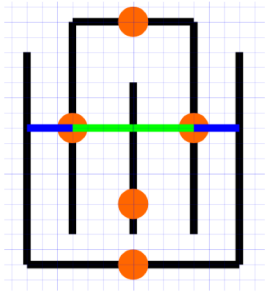
Advanced Power Module Packaging for WBG Devices

Circuit Schematic

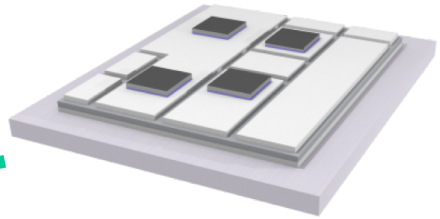


THREE-LEVEL FULL BRIDGE SIC MODULE

Layout template



Select substrate and components



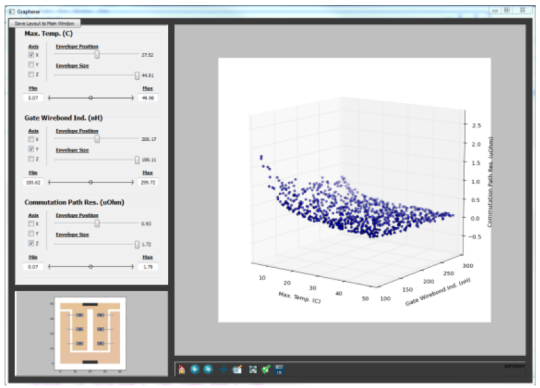
Assign performance measures (objectives)

Step 3: Add Performance Measure

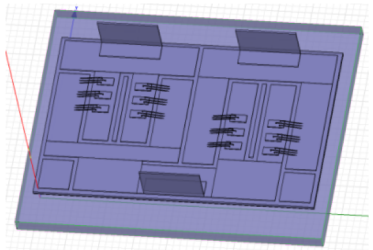
	Max. Temp.	Thermal	Max	X
	Loop Ind.	Electrical	Inductance	X
	Loop Res.	Electrical	Resistance	X
	Sub. Cap.	Electrical	Capacitance	X

Perform Layout Optimization

Explore solution set



Export solutions



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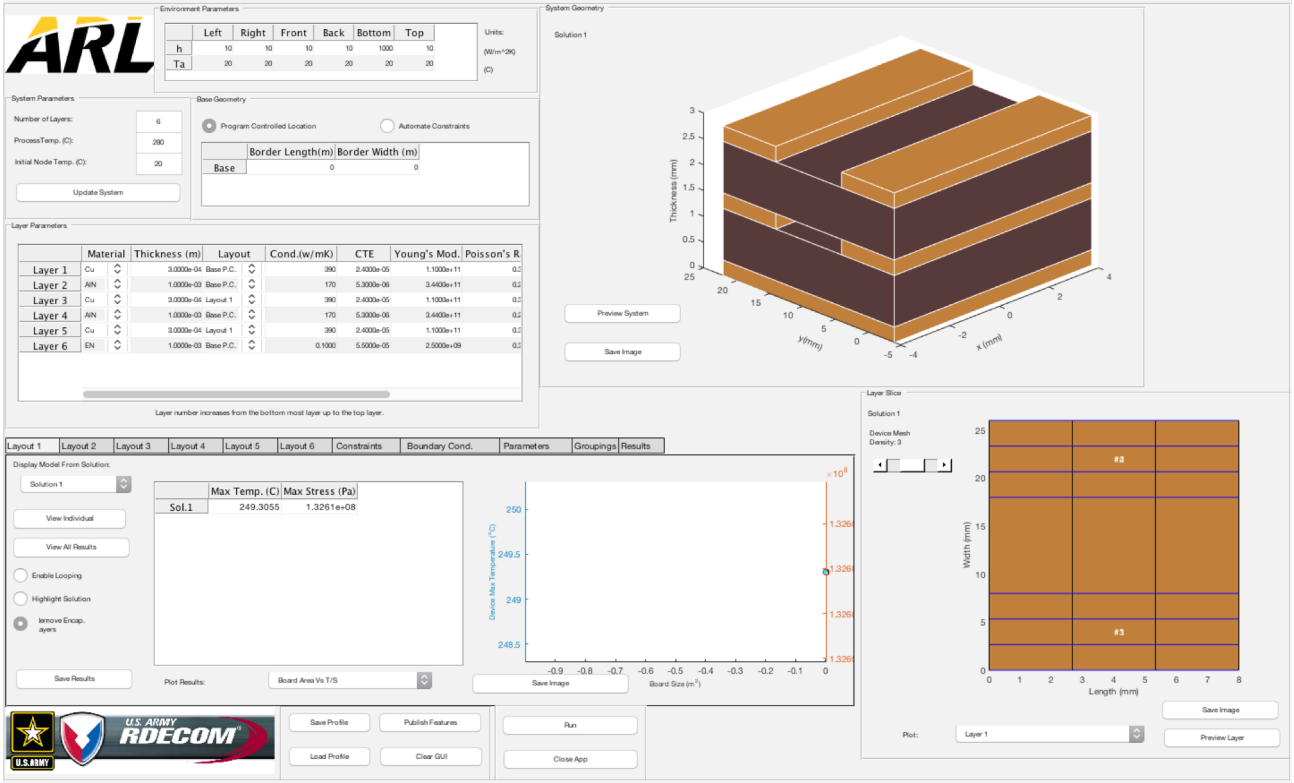
ARL ParaPower

Advanced Power Module Packaging for WBG Devices



L. Boteler, DevComm, S. Miner, USNA

Highlight:

- ***Fast thermal estimation***
- ***Thermal impedance based***
- ***No FEA simulation involved***
- ***Both thermal steady state and dynamic analyses***

Summary

- **Advanced packaging is the key in WBG power conversion**
- **New packaging architectures/material system are in high demand**
- **Converter (PEBB) level packaging is as important as module packaging, which reflects WBG impacts at system level**
- **Multi-disciplinary co-design gives possibility for global optimization**

Back Up