Automotive Power Module Packaging: Issues and Technologies

Zhenxian Liang, Fred Wang, Laura Marlino
Organization: ORNL
Email: liangz@ornl.org
Phone: 865-946-1467

APEC'11, Special Session 2.1
March 8, 2011

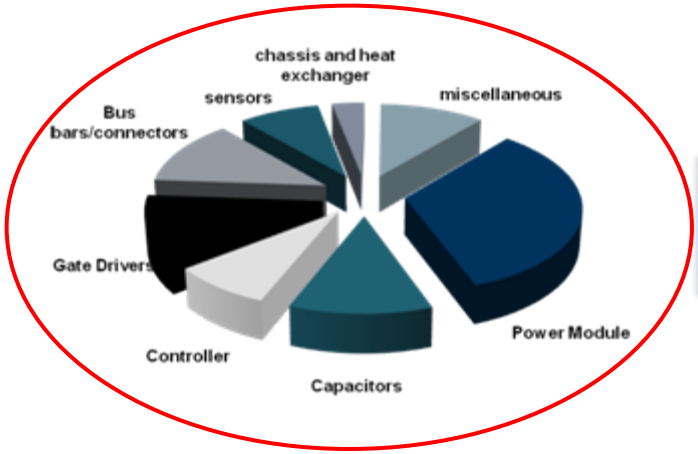
FreedomCAR & Fuel Partnership

U.S. DEPARTMENT OF ENERGY

This presentation does not contain any proprietary or confidential information

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

ORNL Power Electronics Packaging Program



Power electronics System: Constitution and cost breakdown

Reduce Dependence on Oil
Via Electrification of Vehicle Drives

Requirements: 55 kW peak for 18 sec; 30 kW continuous; 15-year life

Technology Targets

Year	Traction Drive System ($/kW)	Traction Drive System (kW/kg)	Traction Drive System (kW/l)	Traction Drive System Efficiency	Power Electronics ($/kW)	Power Electronics (kW/kg)	Power Electronics (kW/l)	Motors ($/kW)	Motors (kW/kg)	Motors (kW/l)
2010	19	1.06	2.6	>90%	7.9	10.8	8.7	11.1	1.2	3.7
2015	12	1.2	3.5	>93%	5	12	12	7	1.3	5
2020	8	1.4	4	>94%	3.3	14.1	13.4	4.7	1.6	5.7

Challenges

size cost weight

Research Areas

Power Electronics
- Innovative topologies
- Temperature-tolerant devices
- Packaging
- Capacitors
- Vehicle charging

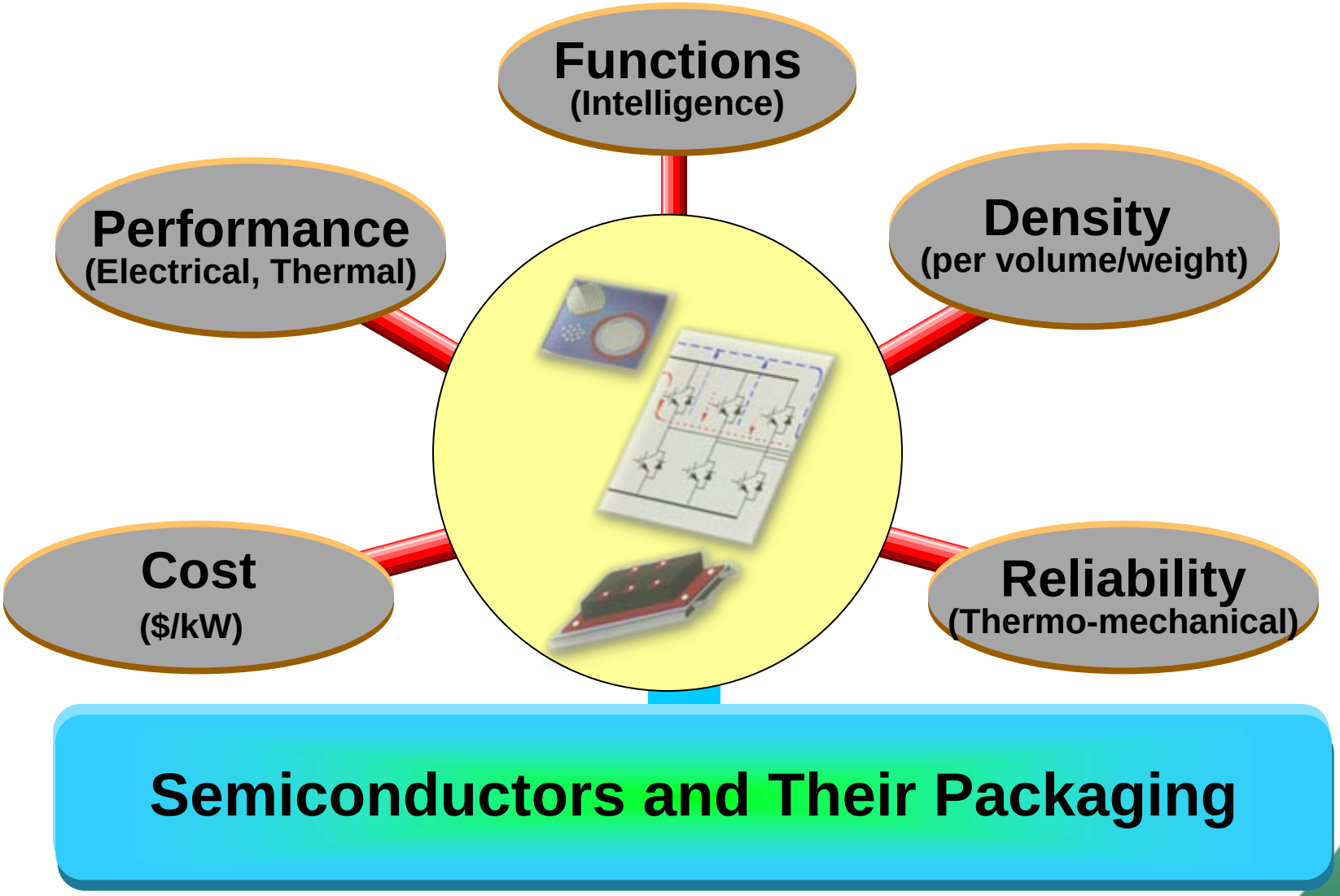
Electric Machines
- Permanent magnet (PM) motors
- Magnetic materials
- High-performance non-PM motors
- New materials

PEEM Thermal Management
- Thermal system integration
- Heat transfer technologies
- Thermal stress and reliability

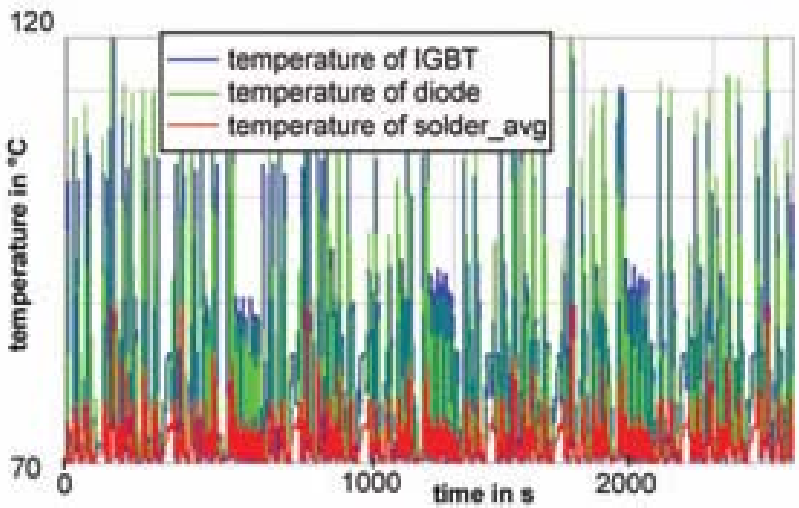
Traction Drive System
- Benchmarking technologies
- Innovative system designs

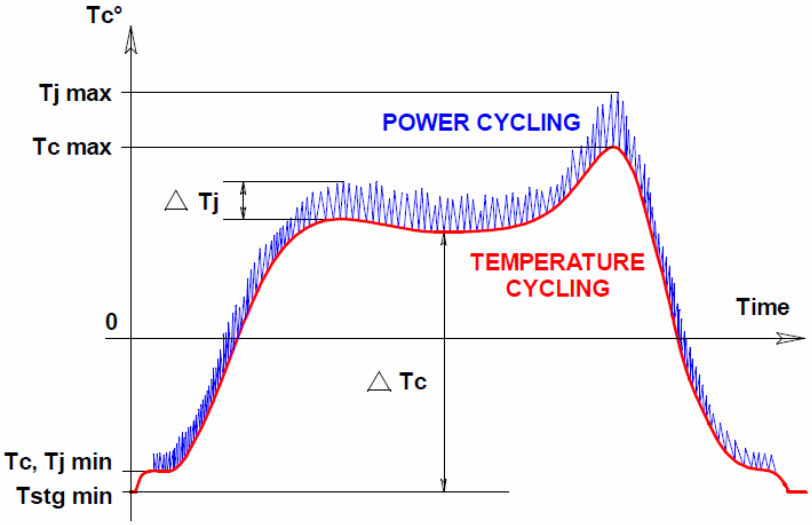
Power electronics module packaging is one enabling technology for performance improvement and cost reduction

Automotive Power Module Qualification



Automotive Power Module Reliability Requirement



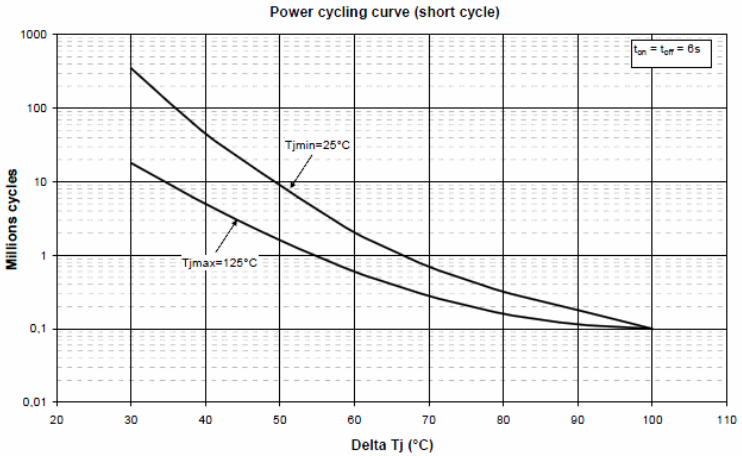


27,000 Power cycles @ ΔT=100°C, T_{jmax}=150°C
10,000 Thermal cycles @ ΔT=80°C

Thoben M. etal, "From vehicle Drive Cycle to reliability testing of Power Modules," Power Electronics Europe, No.6, 2008, P.21

Temperature / Environment	Reliability
Ambient air -40°C to 135°C	Operational Life 15 years
Coolant water -40°C to 105°C	Power Cycling 30.000 cycles @ ΔT 100°C
Junction -40°C to 175°C	Temperature Cycling
Vibration 10g	1000 cycles
Shock 50g	@ Δ T 165°C

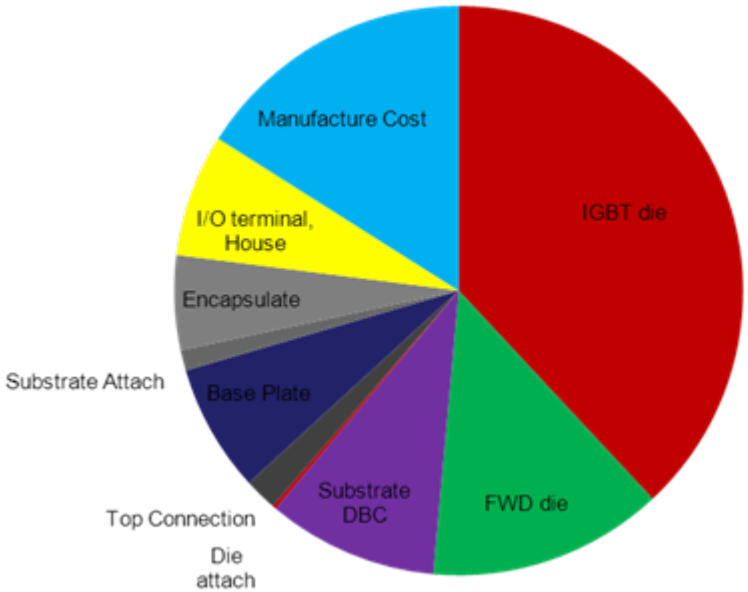
Beckedahl P. etal, "A New Module Concept for Automotive Applications PCIM07

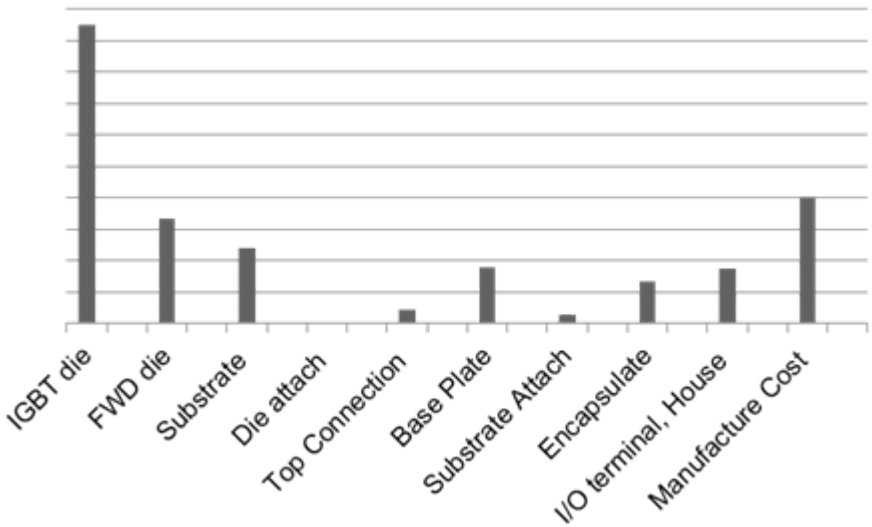


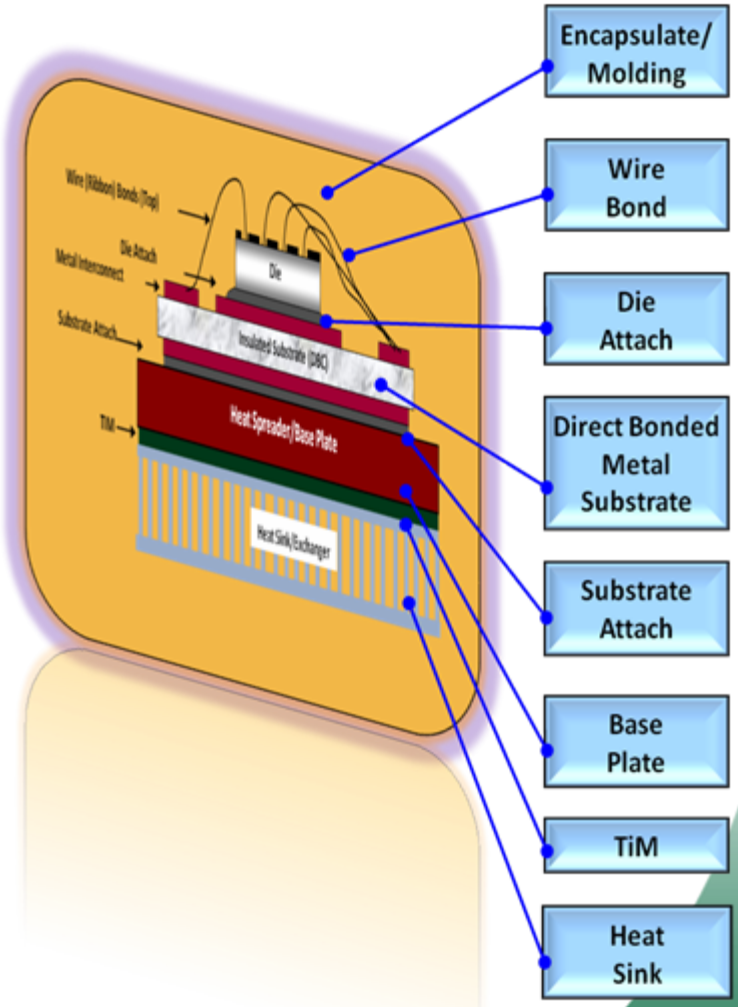
Power device lifetime as a function of delta Tj

*Alain Calmels www.**imaps**france.org/ABSTRACT/.../MICROSEMI_251109.pdf*

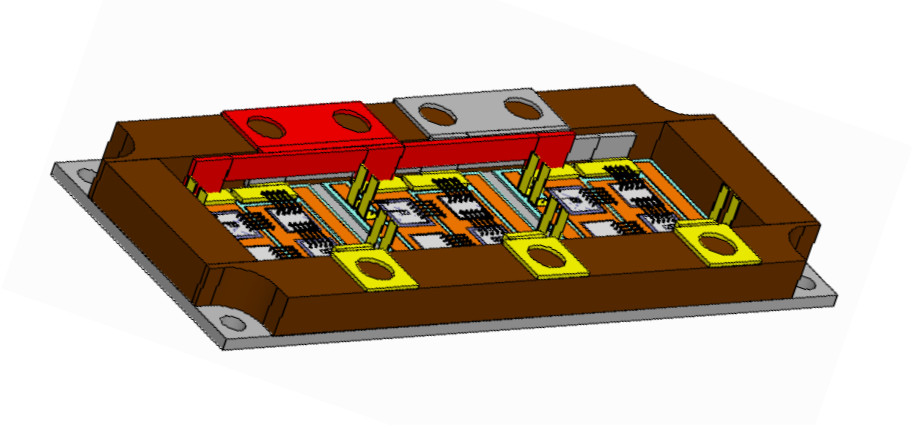
Automotive Power Module Cost Estimation

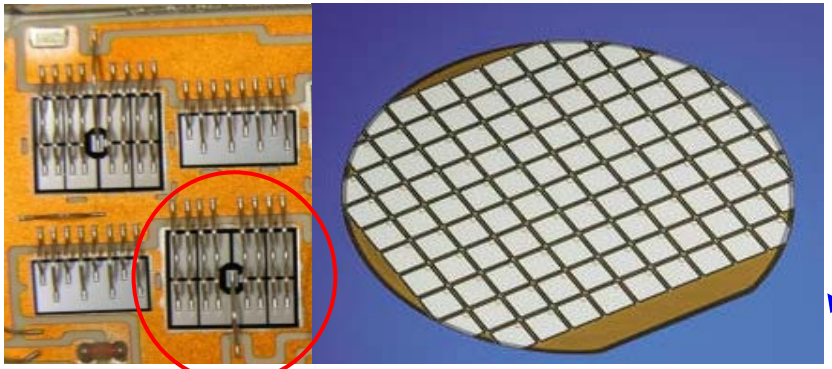






Power Semiconductor Cost Analysis





Semiconductor: Major Cost of Power Module;

Counted by Die Area;

Dependent on Device Structure

Increase Semiconductor Wafer Size (from 6” to 8”);

Barrier: Mechanical Support of Thin Wafer (70um/kV)

From Si to SiC, GaN, etc.

Cost= Die size (S) * $/unit area

Interaction of Power Module Parameters

$$S = P_{Loss} / H_f = \frac{P_{loss} \bullet \theta_{ja,sp}}{(T_j - T_a)} = \frac{\eta \bullet \theta_{ja,sp}}{(T_j - T_a)} \bullet P_{in}(cm^2)$$

S ↓ →

η: $P_{Loss} = \eta \bullet P_{in}$, **Power device loss coefficient** ↓

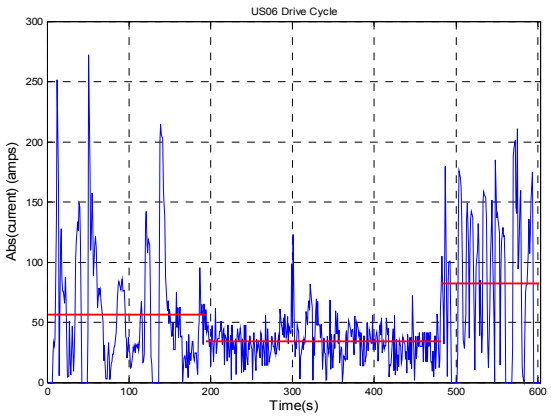
$\theta_{ja,\,sp}$ **Specific Thermal Resistance (C/(W/cm2))** ↓

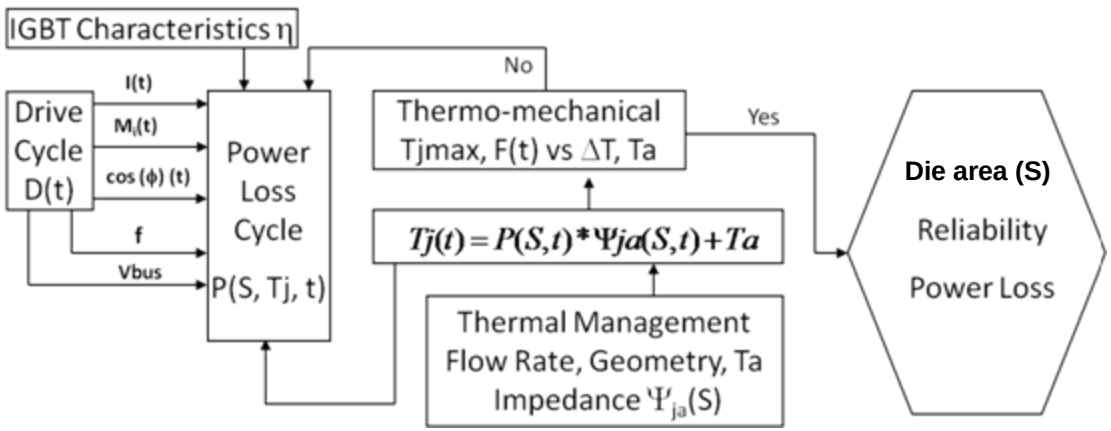
$(T_j\text{-}T_a)$ **Operation Temperature Difference** ↑

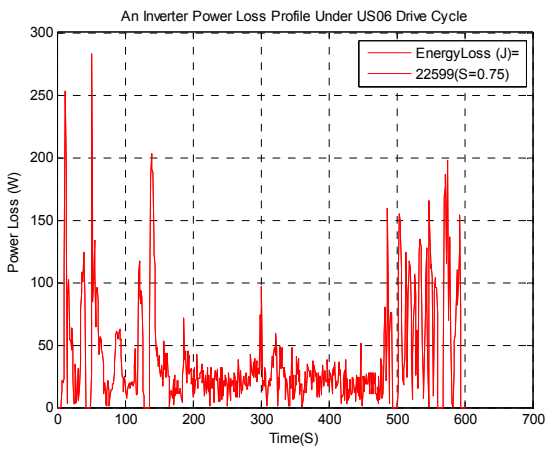
$$\Delta T_j = P_{loss} \bullet \theta_{ja} = \eta \bullet \theta_{ja} \bullet P_{in}(°C)$$

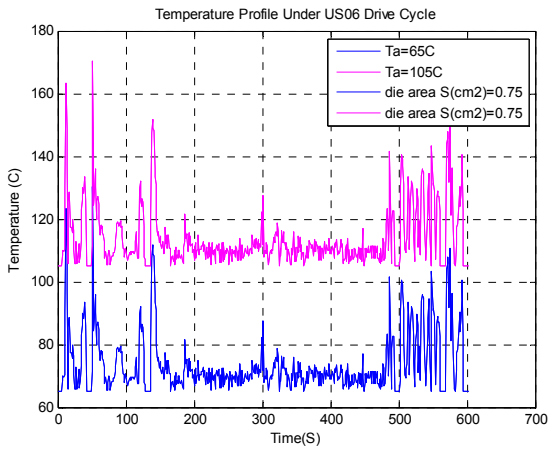
$$T_j \leq T_{j\,\max}$$

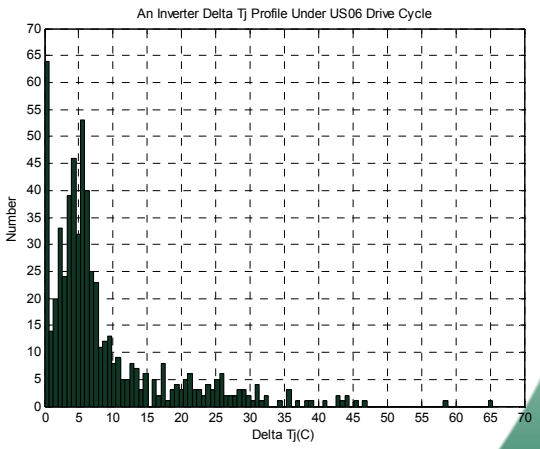
Automotive Power Module: Comprehensive Design



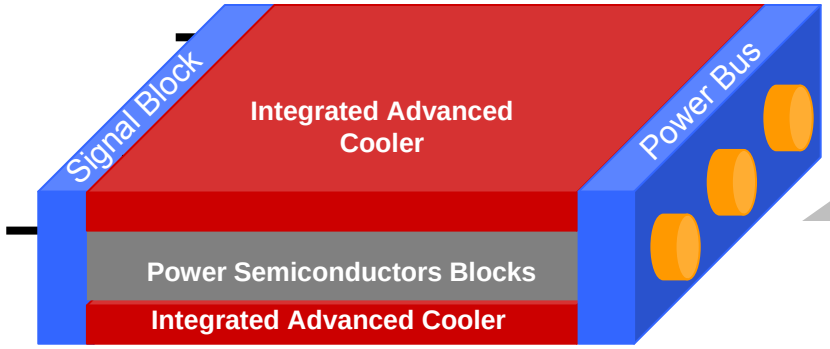








Packaging Paradigm Shift and Challenges



High Temperature Robustness

High TC/PC, Reliability

Highly Efficient Cooling

Cost Effective Manufacturability

Structural Optimization

Double sided Electrical Interconnection;

Integrated cooling (plus Microchannel, spray, jet, phase change, etc)

CTE Matching

CTE modified Materials (AlSiC, Cu-x, Al-x, Si3N4),

Structure/buffer optimization

HT Material Integrity

High-melting bonding (Ag, Au and alloys); Inorganic encapsulate (glass);

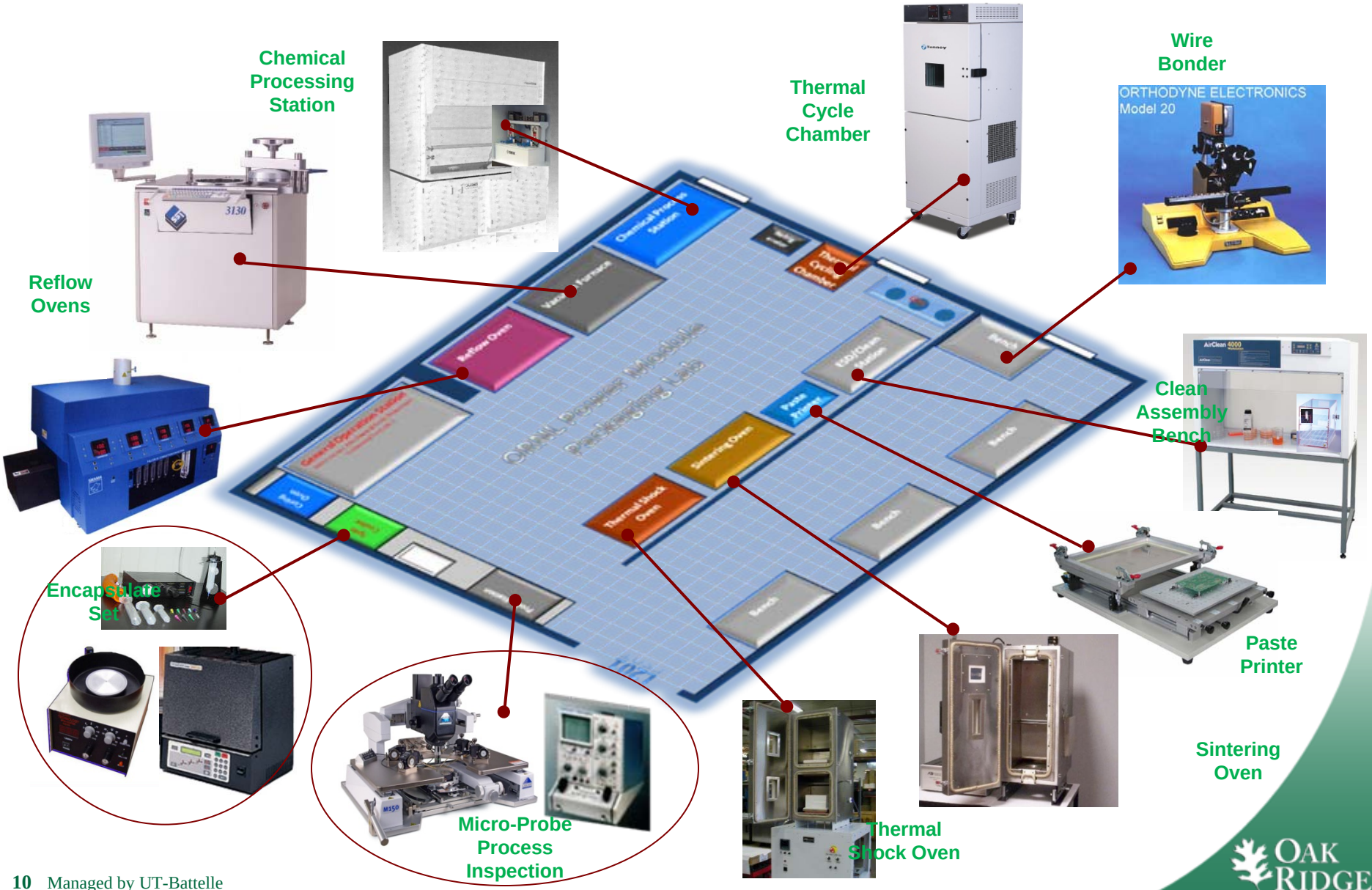
Nano Electrical and Thermal materials

Processing Advance

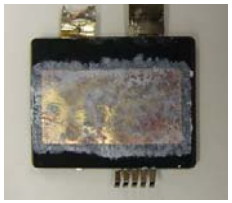
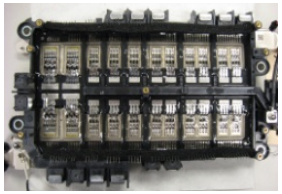
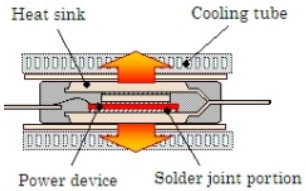
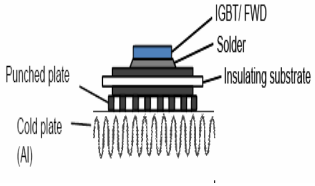
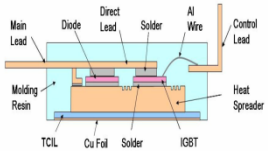
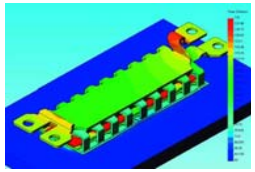
Reflowing, Brazing /Sintering, Transient liquid phase bonding, thermal press

bonding, deposition, Ceramic spray,

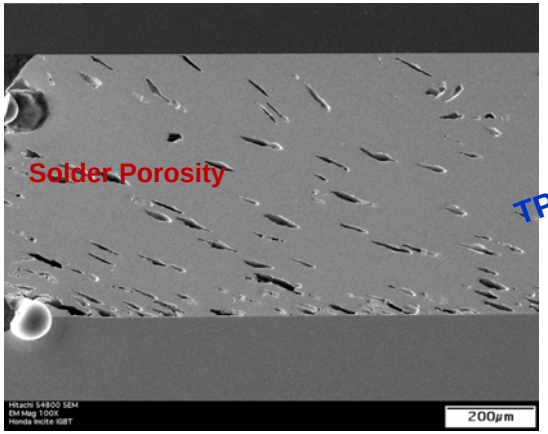
ORNL Advanced Power Module Packaging Lab Facility Layout



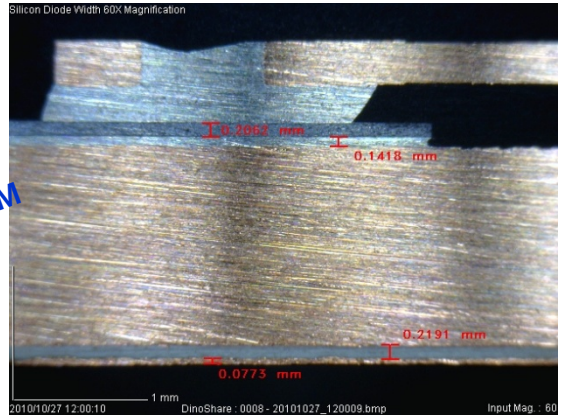
Evaluation of Advanced Automotive Module Packaging Technologies

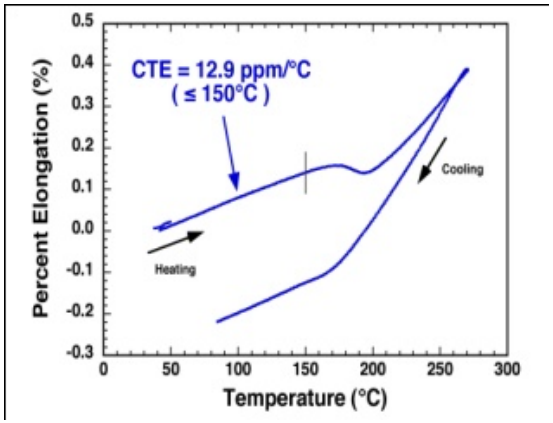
	Toyota LS600	Toyota Prius III	Infineon Hybridpack2	Mitsubishi TPM	Semikron SKiM
Module					
Features					
Advantage	• Double sided planar interconnection; • No baseplate; • Double sided cooling.	• Direct bond cooler; • No base plate; • No TiM layer; • Al Ribbon bond.	• Direct cooled base plate; • No TiM layer; • Integrated cooler.	• No DBC substrate; • Phase leg unit; • Direct planar lead bond;	• No base plate; • Press contact; • Ag sintered die attach.
Disadvantage	• Complex inverter (electrical and thermal) assembly; • Ceramic slice insulation and double TiM layers.	• Stress relax buffer layer worsen thermal conductivity; • Large electrical parasitic parameters.	• Difficulty in pin fin manufacture; • Large electrical parasitic parameters; • Difficult integration of cooler.	• Double TiM layers; • Poor thermal of TCIL; • Module level assembly needed.	• Mechanical integrity concern; • Large electrical parasitic parameters; • Poor TiM layer uniformity.

Microstructure and Mechanics Analysis of Packaging Constitution

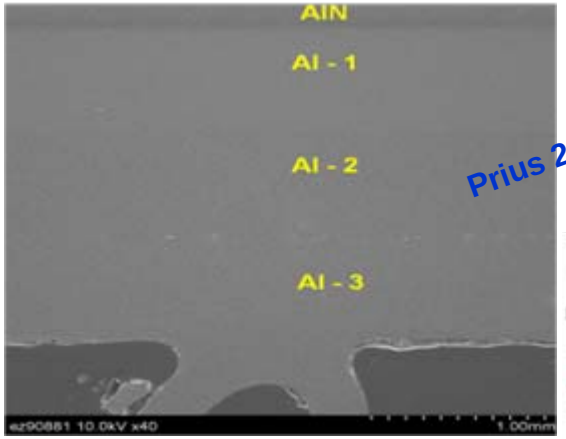


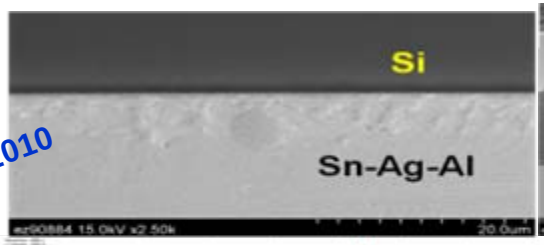
TPM

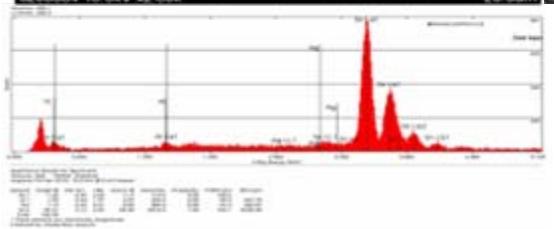




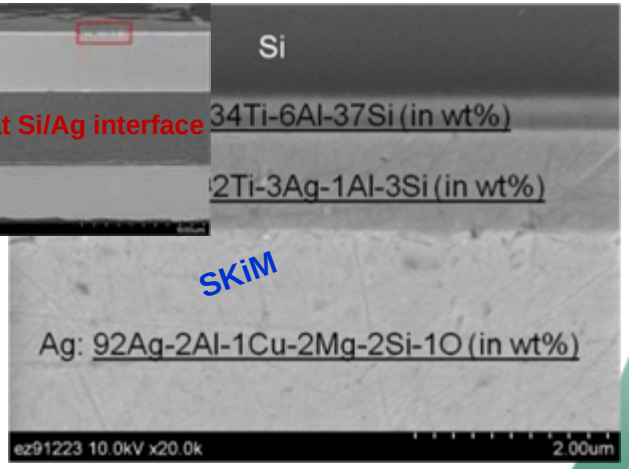
Prius 2010





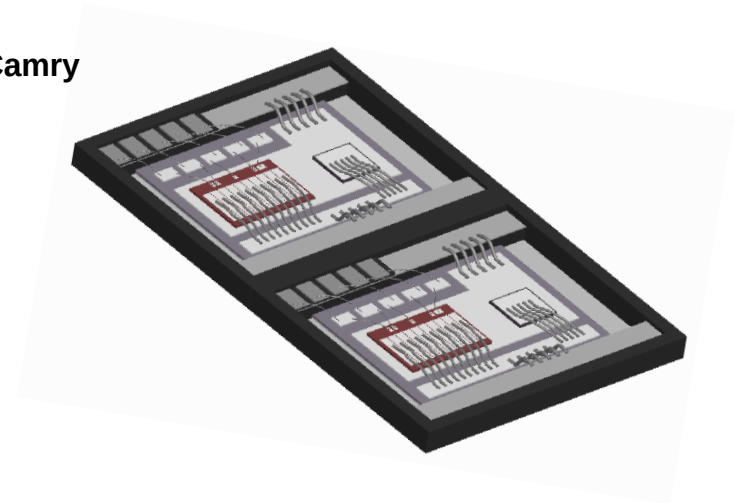


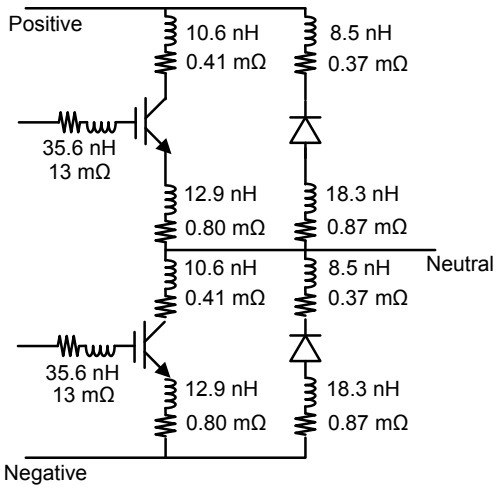
SKiM



Packaging Electrical Parasitic Parameters Extraction

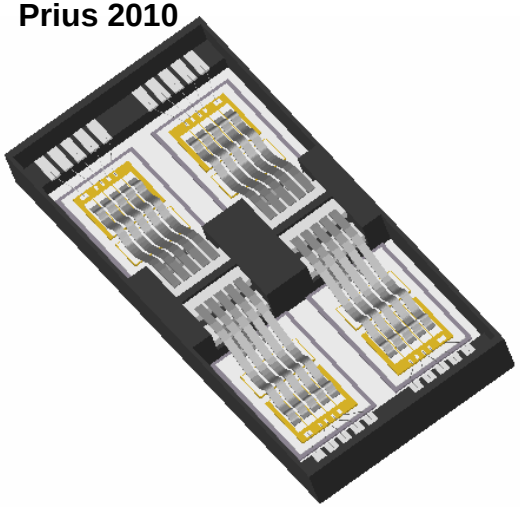
Camry

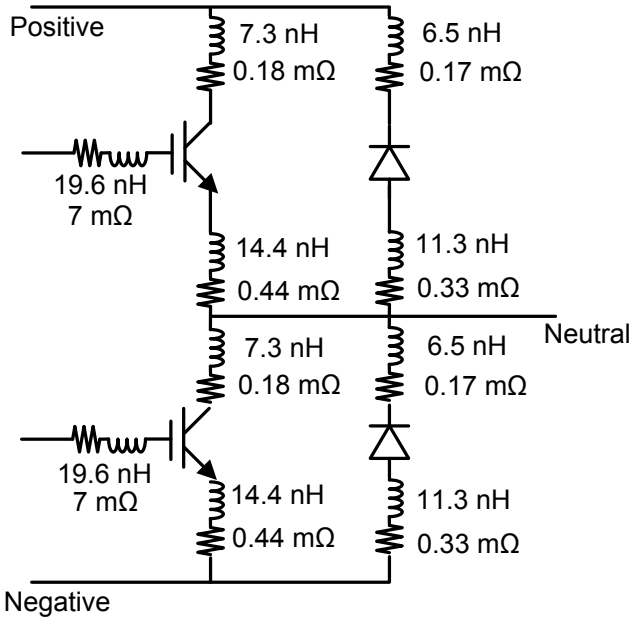




L=50.3nH R=2.35mΩ

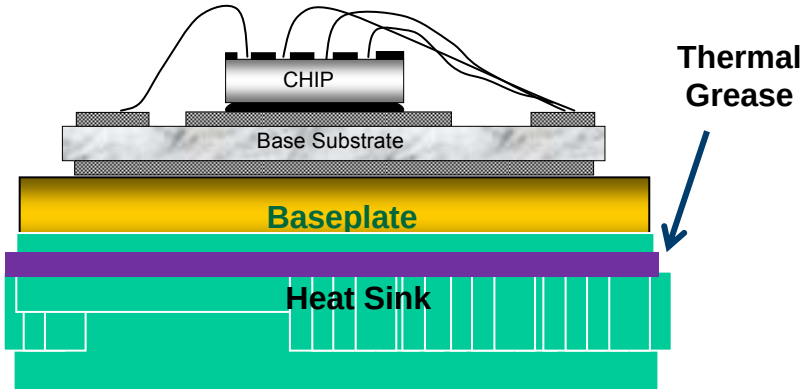
Prius 2010

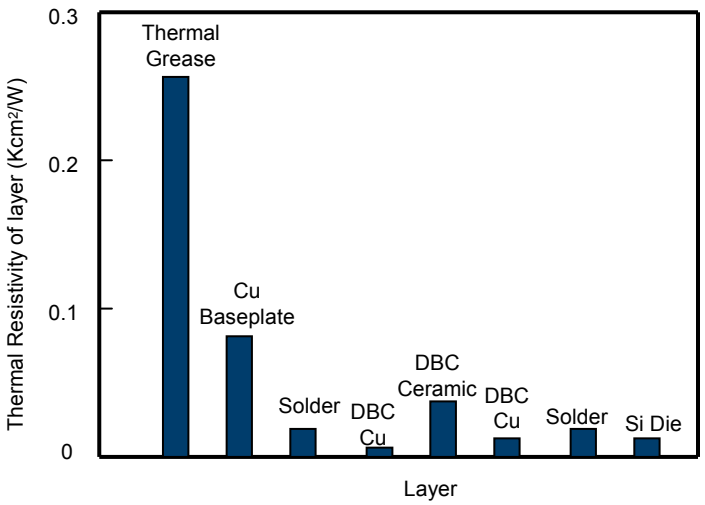


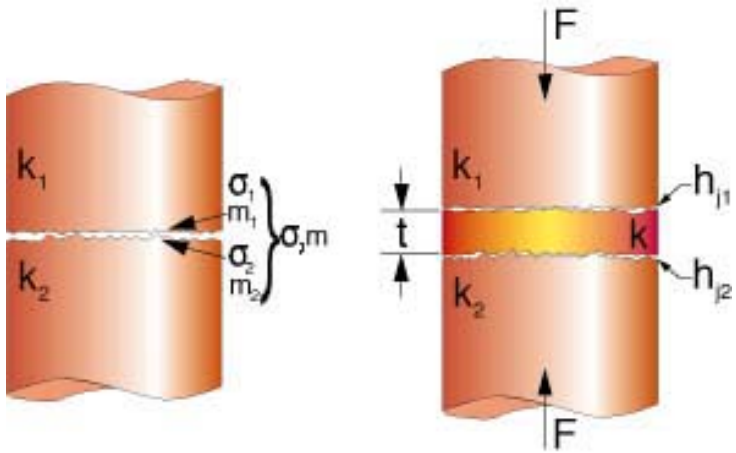


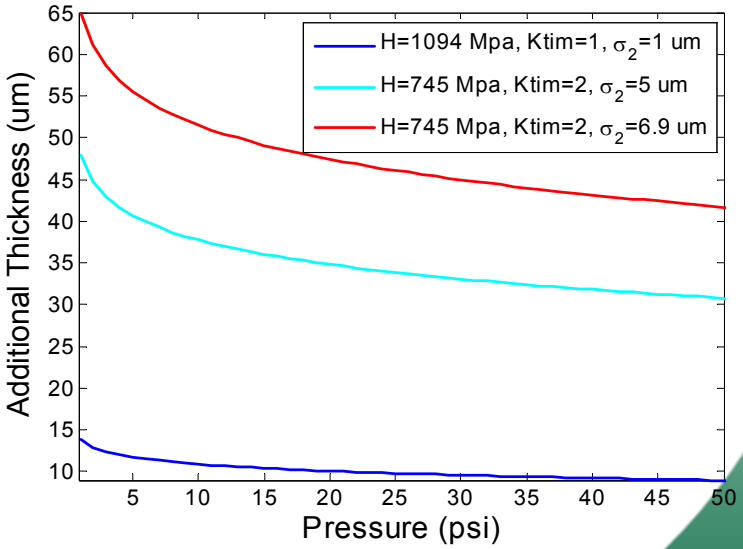
L=39.5nH
R=1.12mΩ

Thermal Resistance Simulation In Power Module

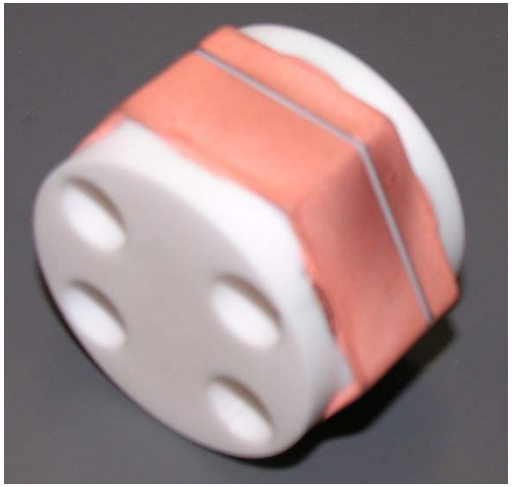


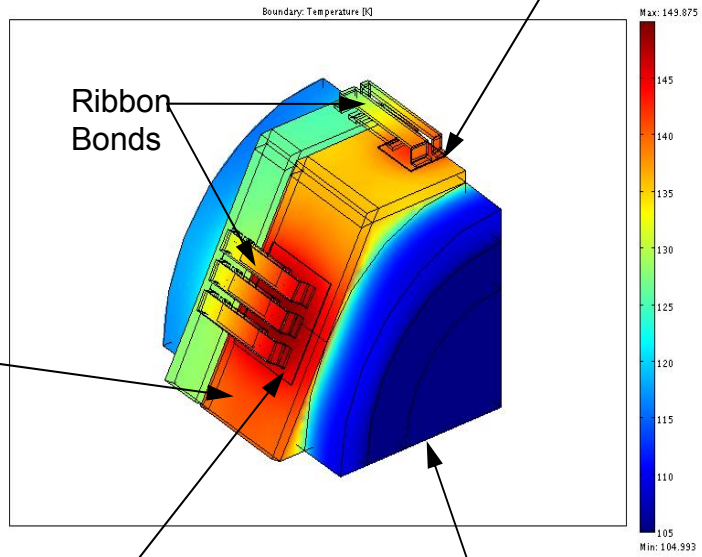






Integrated Cooling Power Module





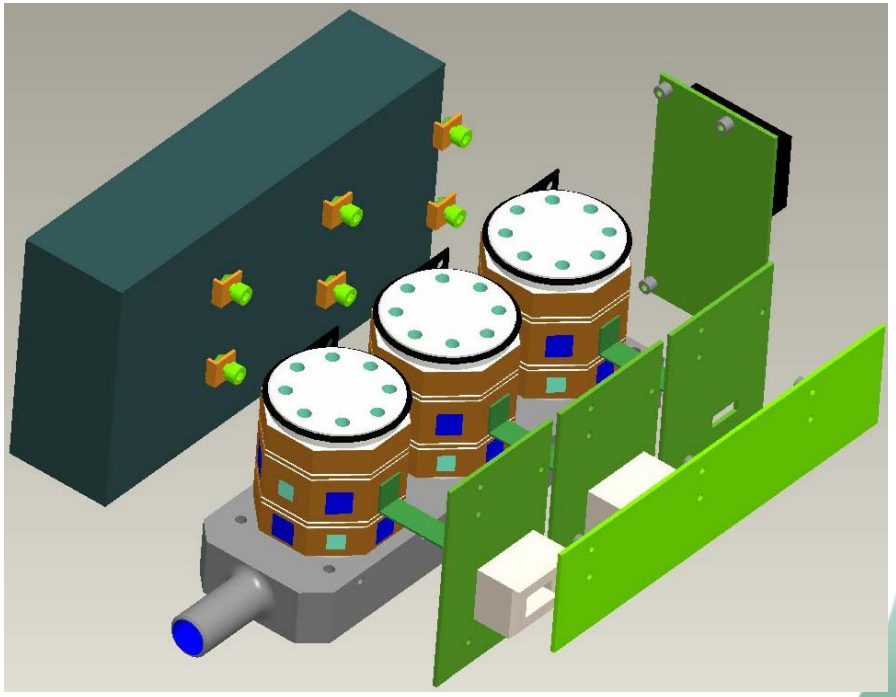
Diode

Ribbon Bonds

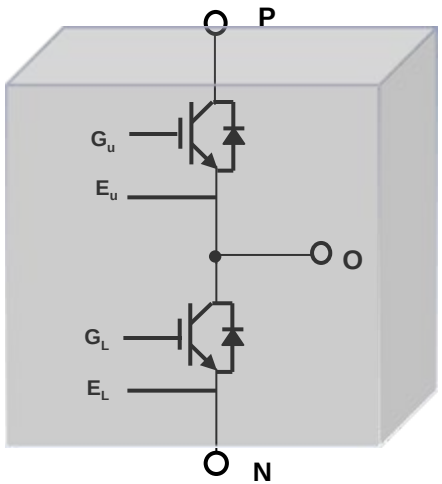
Copper Cladding

IGBT

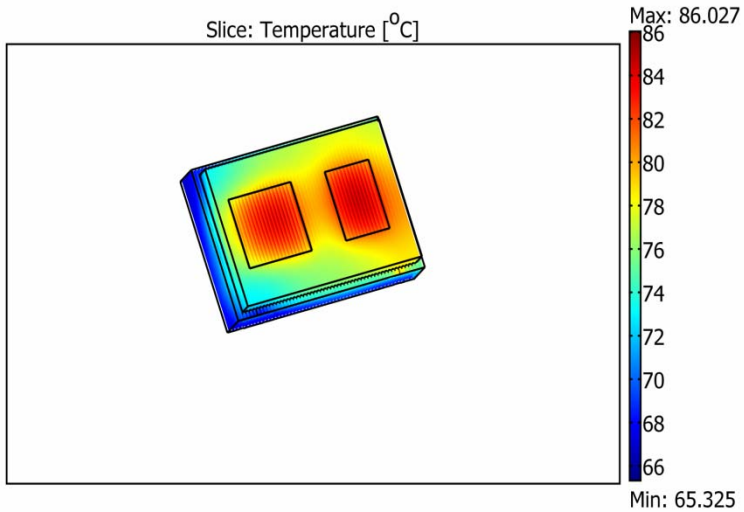
Coolant Channel



An Integrated Phase Leg Packaging Design



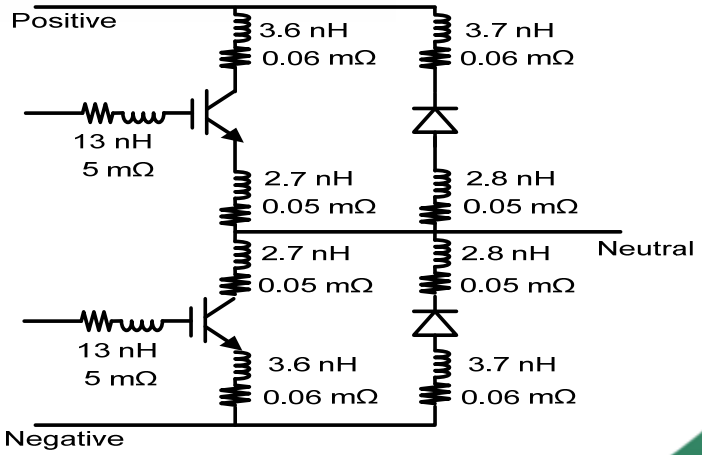
ORNL Advanced Power Device Packaging Structure



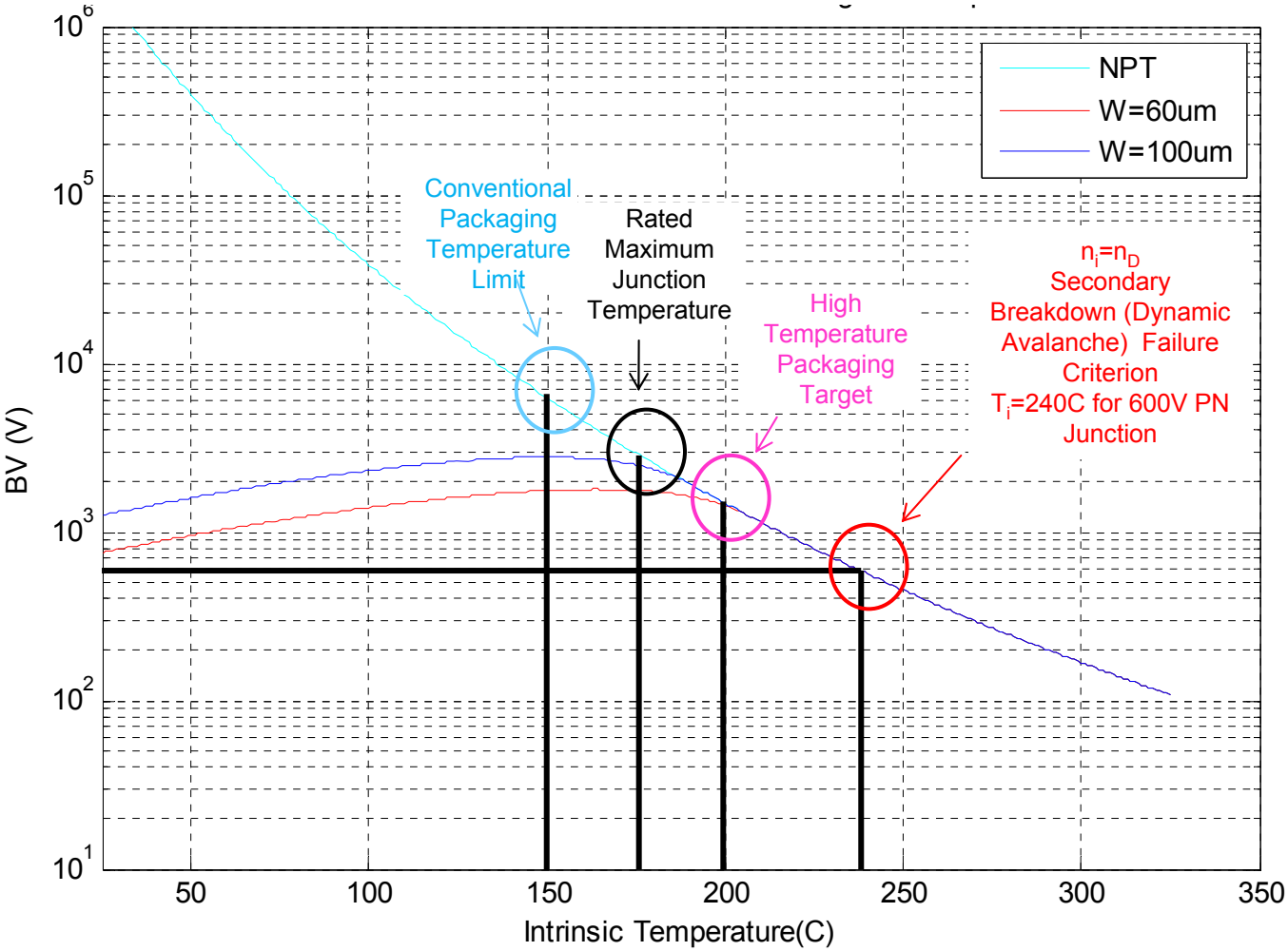
60% Thermal Performance Improvement

L=12.8nH
R=0.22mΩ

Electrical Parasitic Parameters (20-30% of Prius)

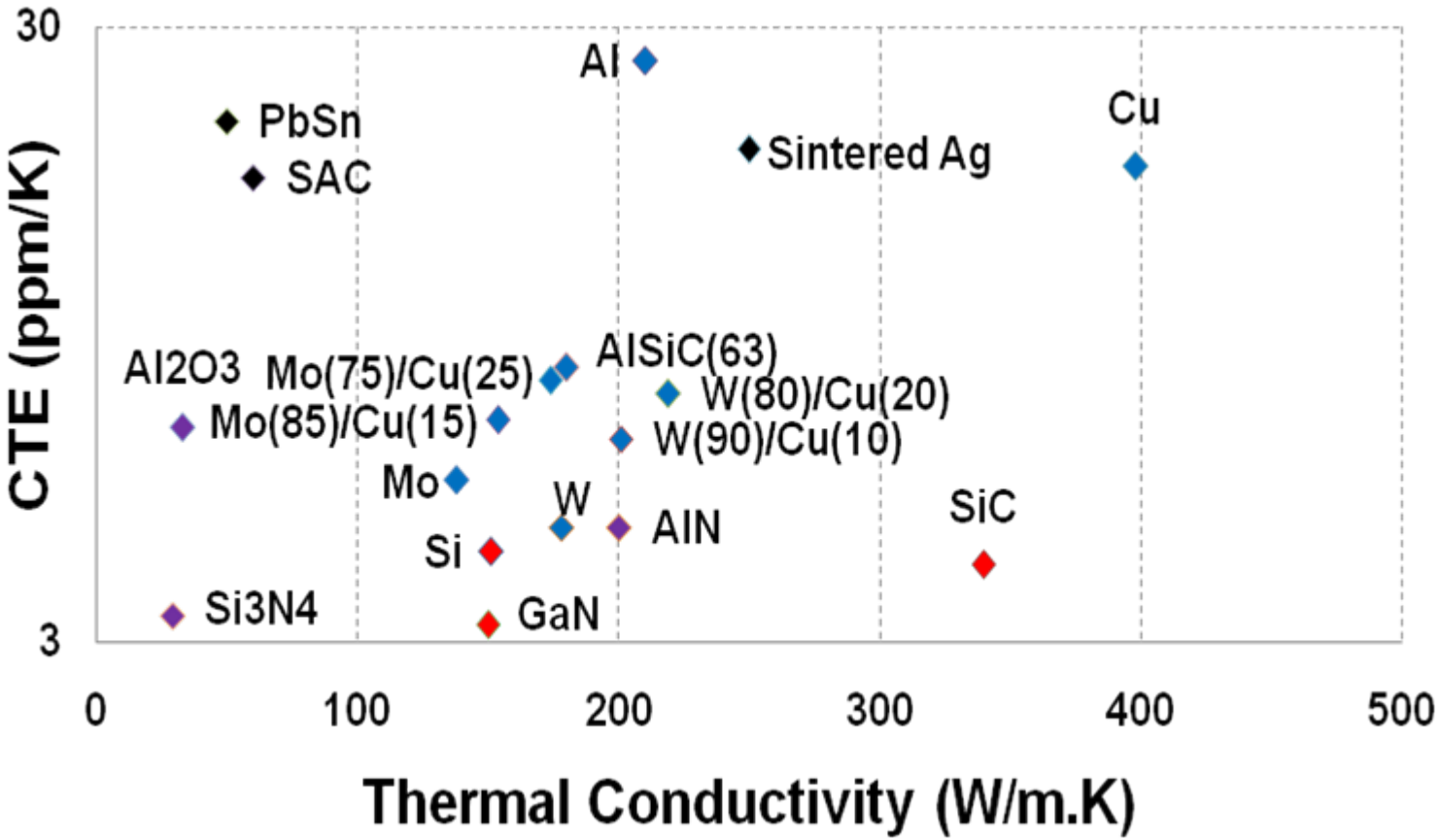


High Temperature Limit of Si Switch

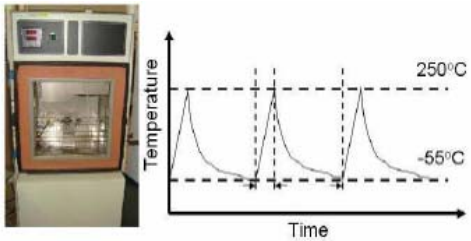


High Temperature Packaging: Material CTE Matching

200°C Reliable Operation Temperature



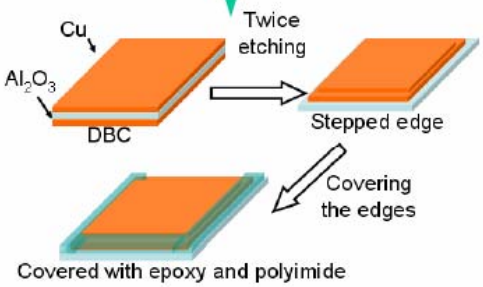
High Temperature Packaging: Structure Optimization



Cycle profile: -55ºC to 250ºC, 45mins per cycle

Sample	Lifetime
Original AlN DBC	20 cycles
Original Al_2O_3 DBC	30 cycles
Stepped edge AlN DBC	60 cycles
Stepped edge Al_2O_3 DBC	180 cycles
Sealed regular Al_2O_3 DBC	45 cycles
Sealed regular AlN DBC	100 cycles
Sealed Stepped edge Al_2O_3 DBC	1200 cycles
Sealed Stepped edge AlN DBC	1300 cycles

Original DBC failed after 20 cycles



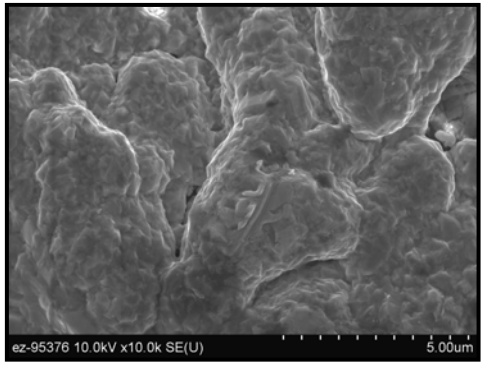
Failed after 1300 cycles

Lifetime **70X**

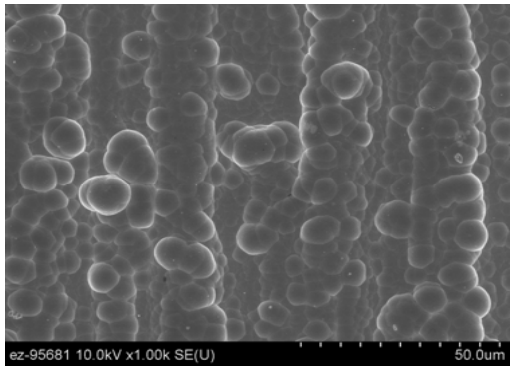
12

Puqi Ning, Ph. D dissertation, Virginia Tech, 2010

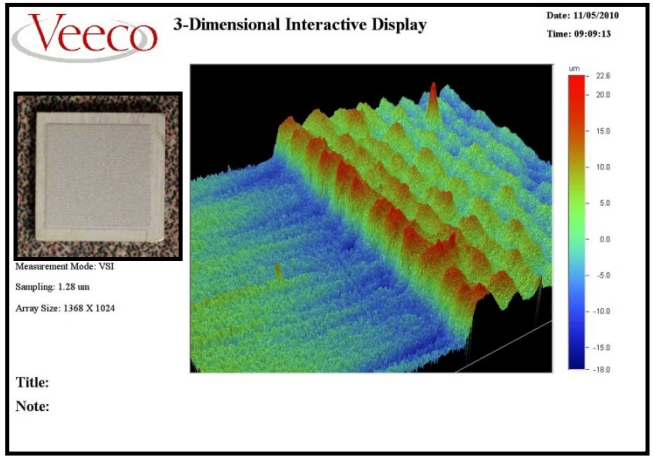
High Temperature Packaging: Die Attachment

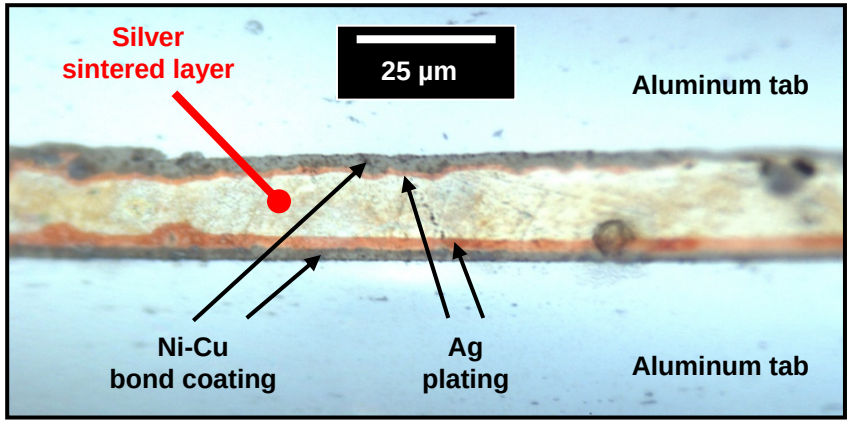


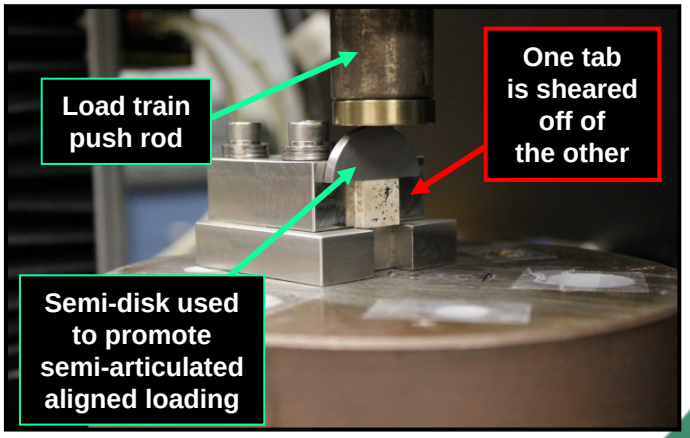
Ag on Cu



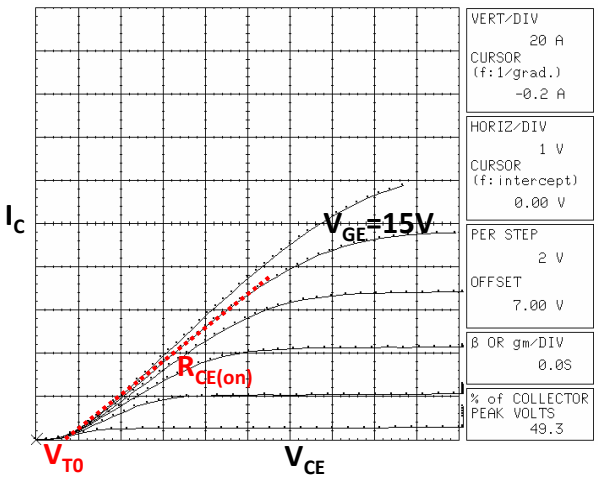
Pd on Al



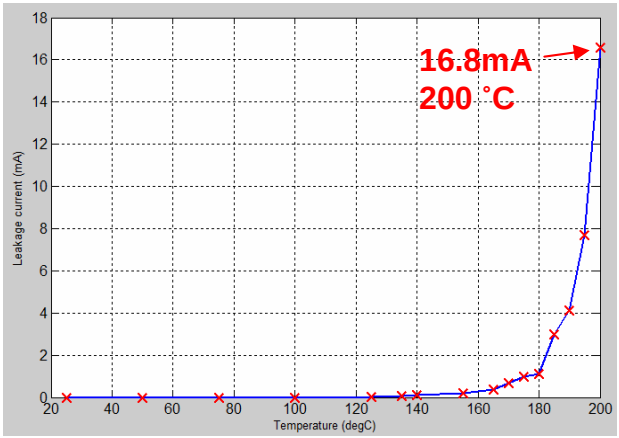




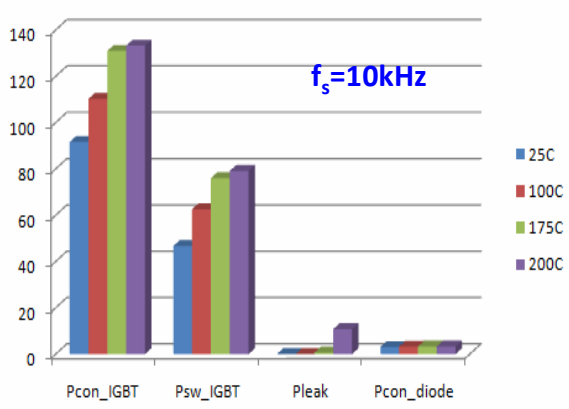
Si IGBT (1200V): High Temperature Operation



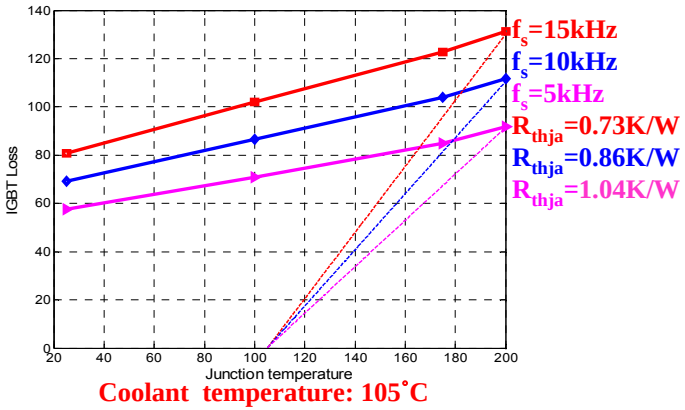
I-V Characterization



Leakage Current at Block State



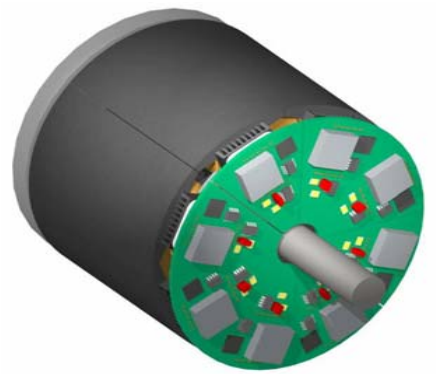
Power Loss vs Temperature

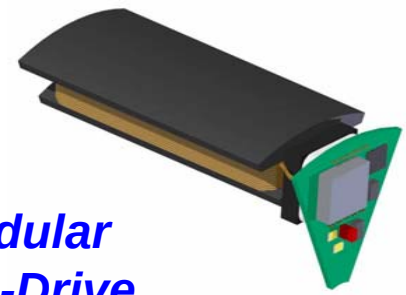


Power Loss vs Thermal Management

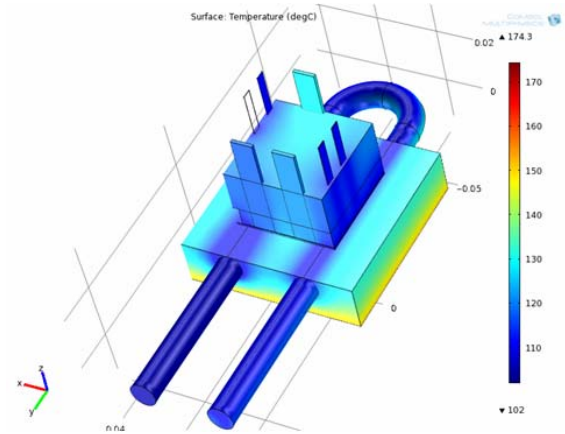
High Power Density Integrated Traction Drive

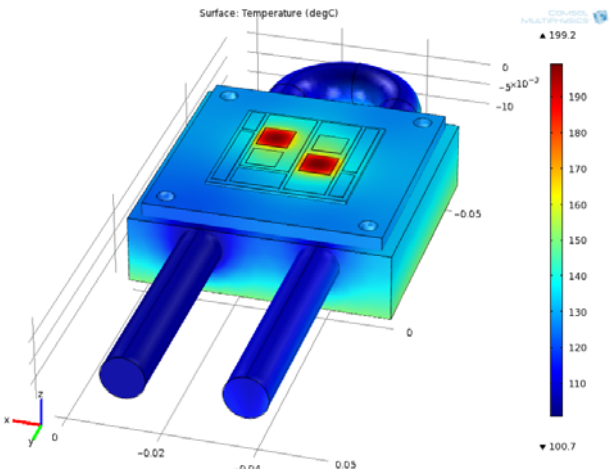
IMMD



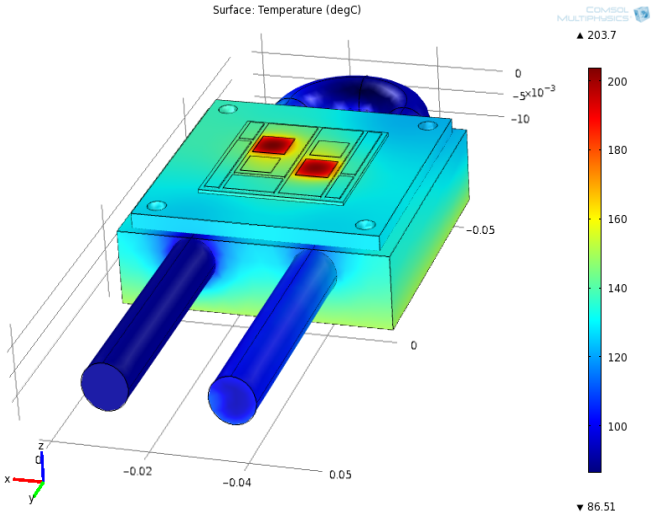


Modular Pole-Drive Unit





(a)105 ˚C water ethylene glycol



(b) 90 ˚C transmission oil

Summary

- Developing power electronics packaging is a vital effort to meet DOE VTP targets in products' performance improvement and cost reduction.
- Advancing packaging technology with materials development, structure optimization and processing innovation.
- Improving cost-effectiveness, efficiency and reliability of power electronics modules by improved electrical performance, reliable high temperature operation, efficient thermal management, highly functional integration and power density.

Acknowledgement

The automotive power electronics packaging works have been primarily supported by DoE under Vehicle Technology Programs. The authors would also like to thank their colleagues, Andrew A. Wereszczak, Randy Wiles, Puqi Ning, Madhu Chinthavali, all with ORNL for the contribution to this presentation

Thanks And Questions?