Development of Packaging Technologies for Advanced Automotive Power Module

Zhenxian Liang, Fred Wang, Laura Marlino

Organization: ORNL
Email: liangz@ornl.gov
Phone: 865-946-1467

APEC 2012, Industry Session 2.3
February 8, 2012

U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy

USDRIVE
DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

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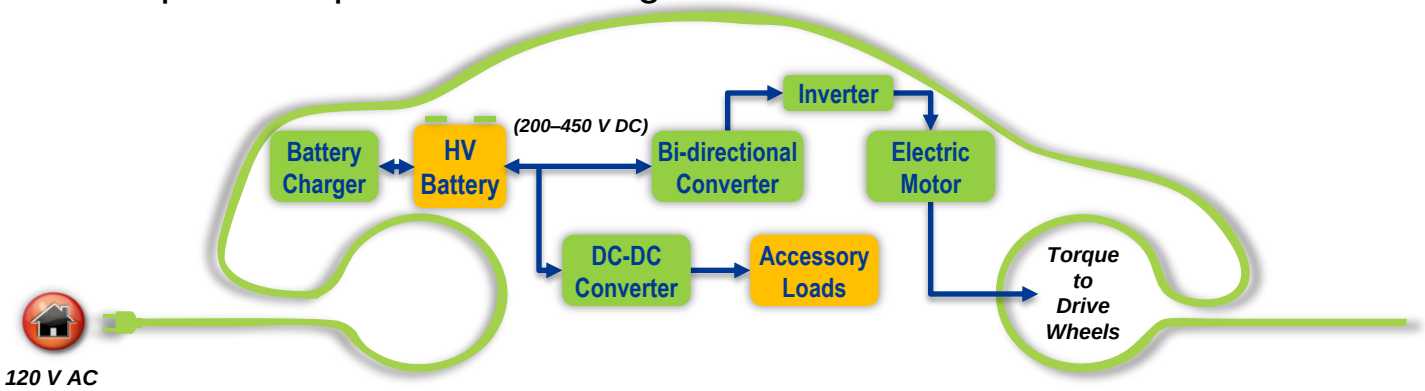
APEEM Components are Critical and Unique to Electric Drive Vehicles

Traction Drive Components
(varies with vehicle architectures)

- ***Battery charger*** – necessary for plug-in and all electric vehicles.
- ***Bi directional boost converter*** – steps up the battery voltage to a higher level when the traction system requires a higher operating voltage than the battery can supply.
- ***Inverter*** – converts direct current (DC) to alternating current (AC) to provide phased power for vehicle traction machines.
- ***Electric motor*** – provides power for driving.



Power Management
(varies within vehicle architectures)

- ***DC-DC converter*** – steps down the high battery voltage to provide auxiliary power busses to operate accessories, lighting, air conditioning, brake assist, power steering, etc.

Challenges for Power Electronics In HEVs/PHEVs/BEVs

http://alternativefuels.about.com/od/2010hybridreviews/ig/2010-Toyota-Prius-photos.-6Hz/2010-Prius-Gen2-Gen3-inverter.htm

Density
(per volume/weight)

Functions
(Intelligence)

Reliability
(Thermo-mechanical)

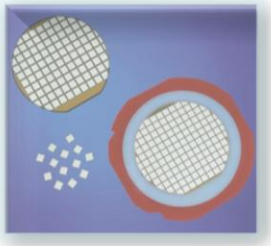
Cost
($/kW)

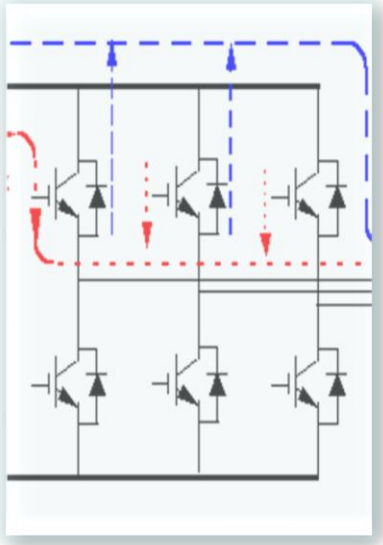
Performance
(Electrical, Thermal)

http://www.motortrend.com/oftheyear/car/1201_2012_motor_trend_car_of_the_year_contenders_and_finalists/photo_255.html

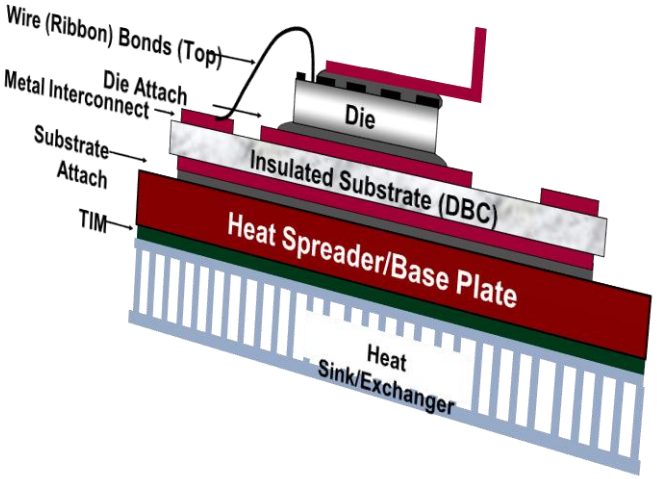
Current power electronics and electric machine technologies must advance to achieve lower cost, smaller and lighter footprints, and higher efficiency to meet marketplace demands.

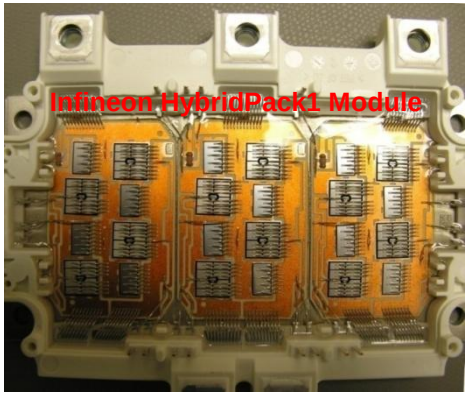
Automotive Power Module Assembly



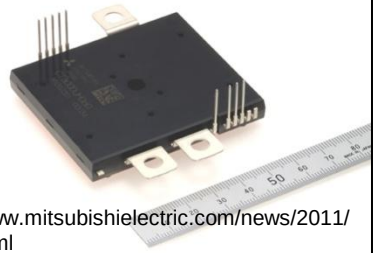


- **Power Semiconductors**
- **Electrical Interconnection**
- **Thermal Management**
- **Mechanical Support**

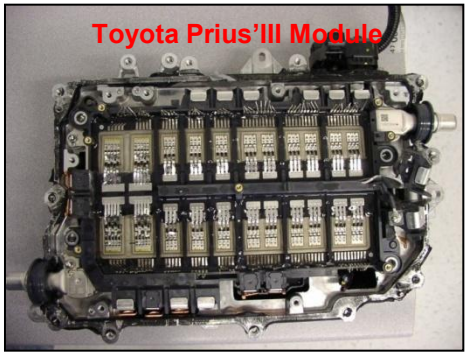




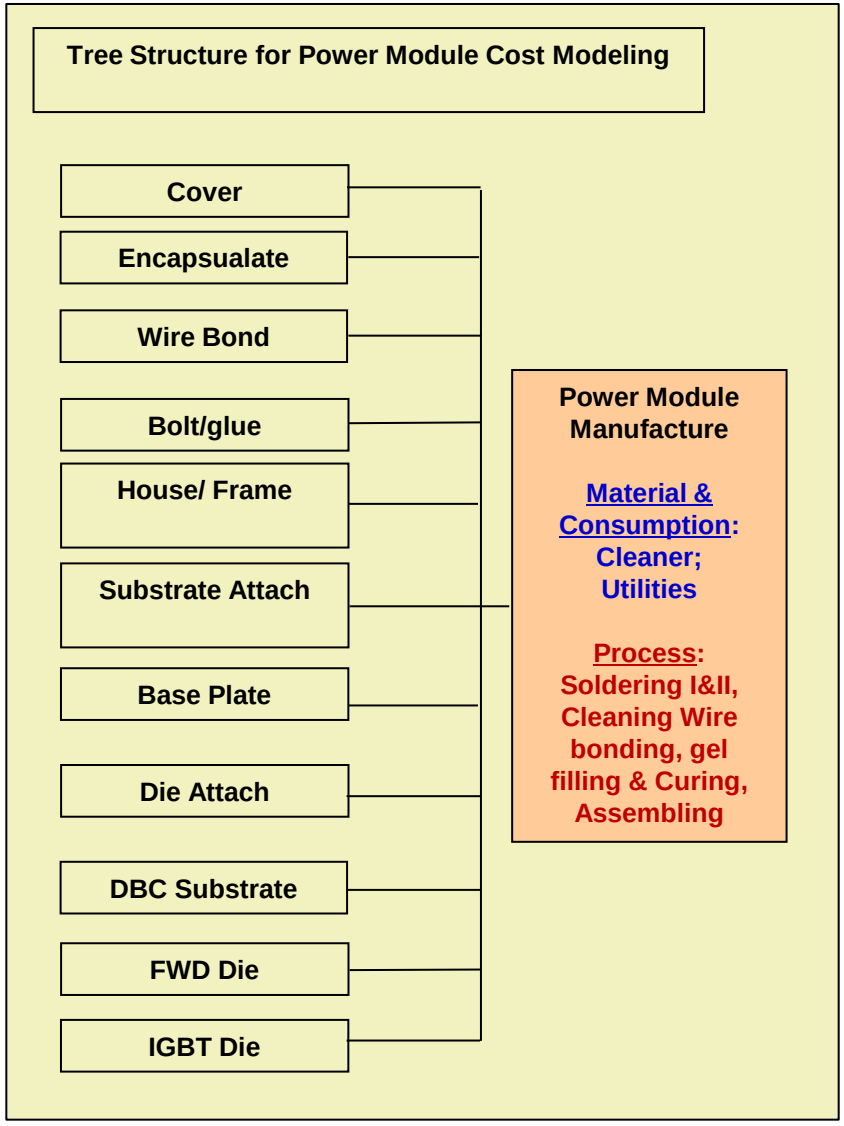
Mitsubishi TPM Module

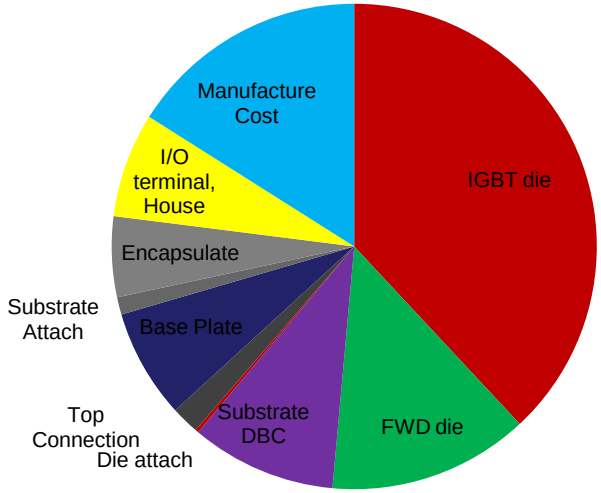


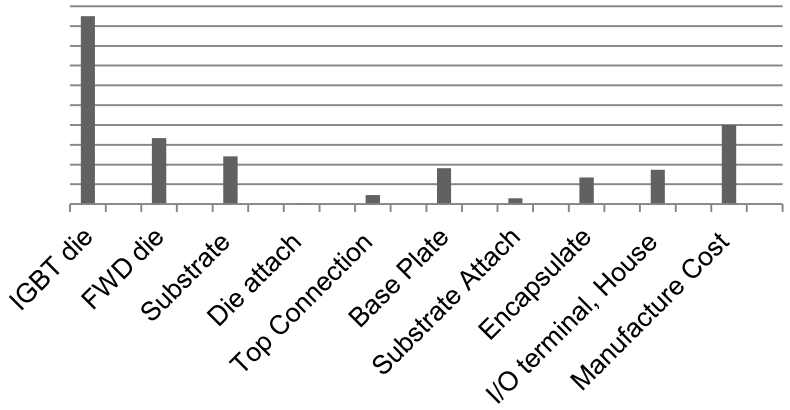
http://www.mitsubishielectric.com/news/2011/0407.html



Automotive Power Module: Cost Estimation







- **Semiconductor Cost**
- **Packaging Manufacture**

Automotive Power Module: Comprehensive Design

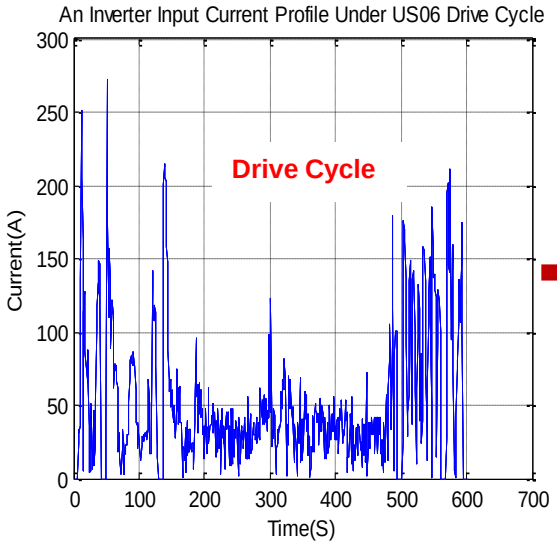
Semiconductor Characterization

$Vce=V_0+r*J=V_0+r*(I/S)$

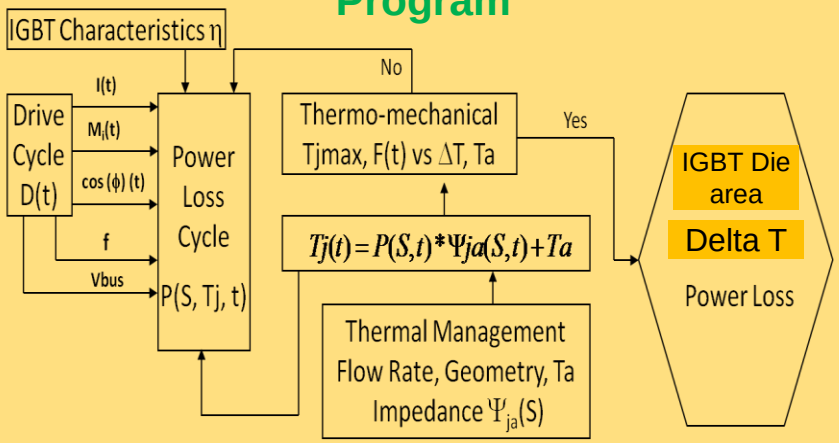
$E_{dswitching}=u*J^2+w*J$

Reliability Characterization

$$N_f(\Delta Tj) = (\frac{A}{\Delta Tj})^B$$



ORNL Power Module Evaluation Program



IGBT Die Area_Cost

Delta T_ Reliability

Power Loss_ Efficiency

Electrical Characterization

Lp, Rp

Thermal Characterization

$$\theta_{ja} = \alpha * S^{-\beta}$$

Development of Power Module Packaging Technologies

High Temperature Robustness

High Electrical Efficiency

Highly Efficient Cooling

Cost Effective Manufacturability

HT Material Integrity

High-melting bonding; Inorganic encapsulate;

Nano Electrical and Thermal materials

CTE Matching

CTE modified Materials;

Structure/buffer optimization

Structural Optimization

Optimized Electrical Interconnection;

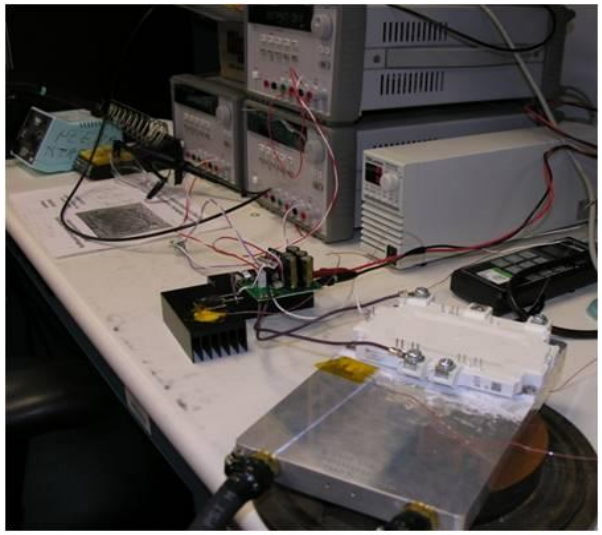
Integrated cooling and advanced mechanism

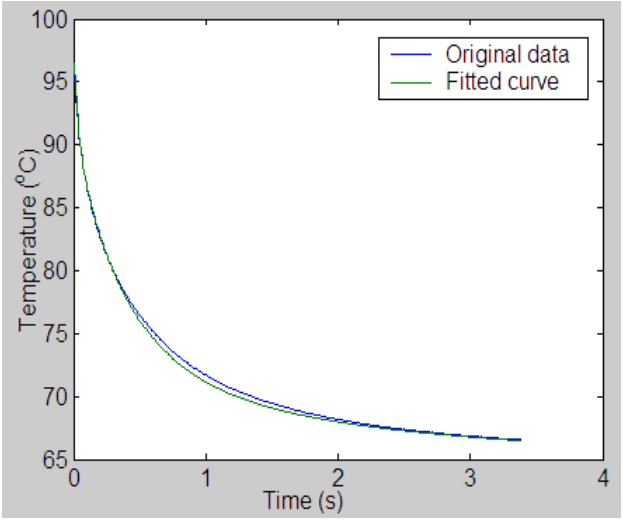
Processing Advance

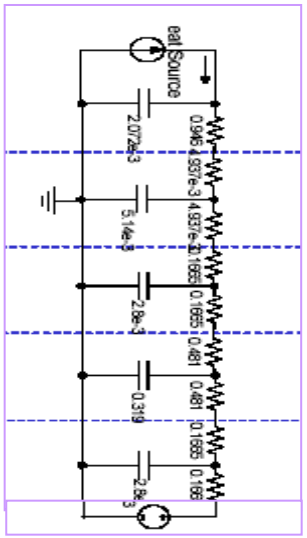
Reflowing, Brazing /Sintering, Transient liquid phase bonding, thermal press

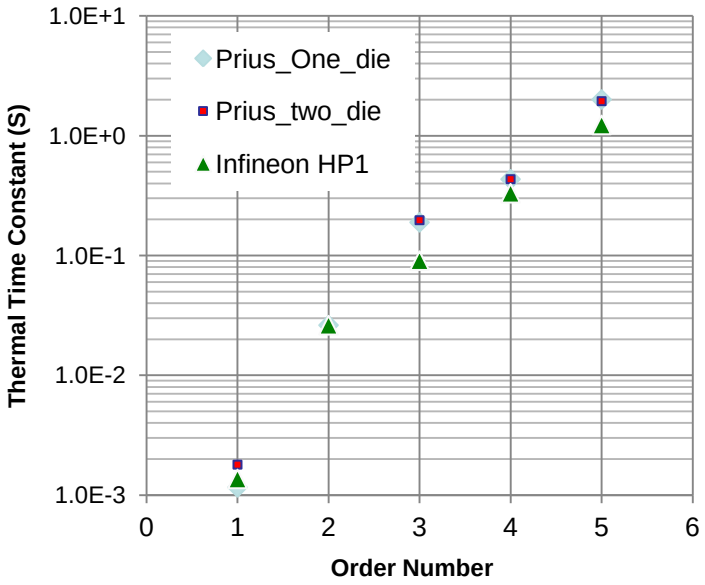
bonding, deposition, etc.

Power Module: Thermal Characterization

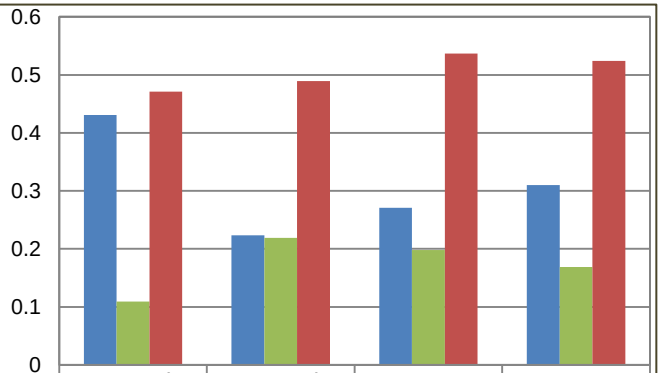






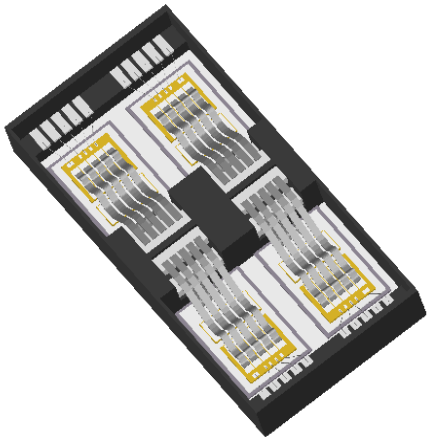


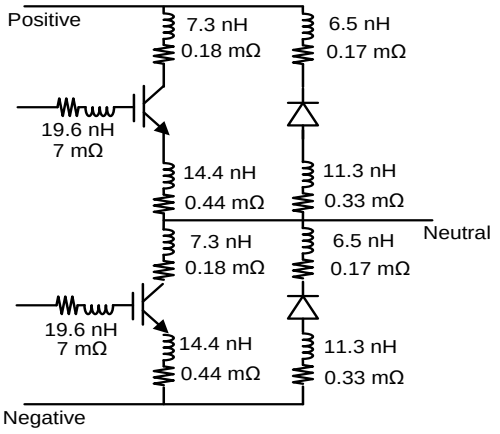
Thermal Resistance Comparison

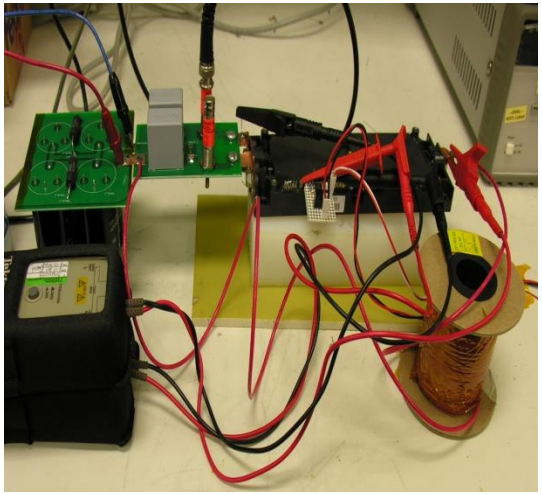


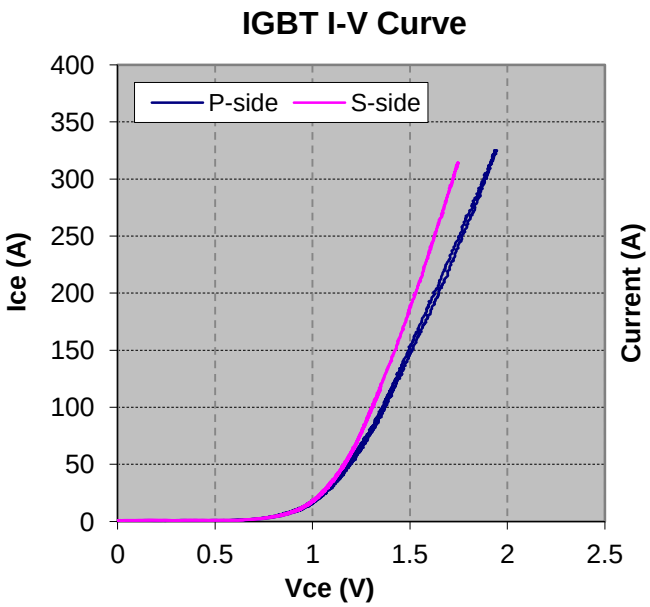
	ToyotaPrius 10_OneDie	ToyotaPrius 10_TwoDie	InfineonHP1	NissanLeaf
Thermal Resitance (C/W)	0.43	0.22	0.27	0.31
Die area (10xcm2)	0.11	0.22	0.20	0.17
Specific Thermal resitance (Cm2.C/W)	0.47	0.49	0.54	0.52

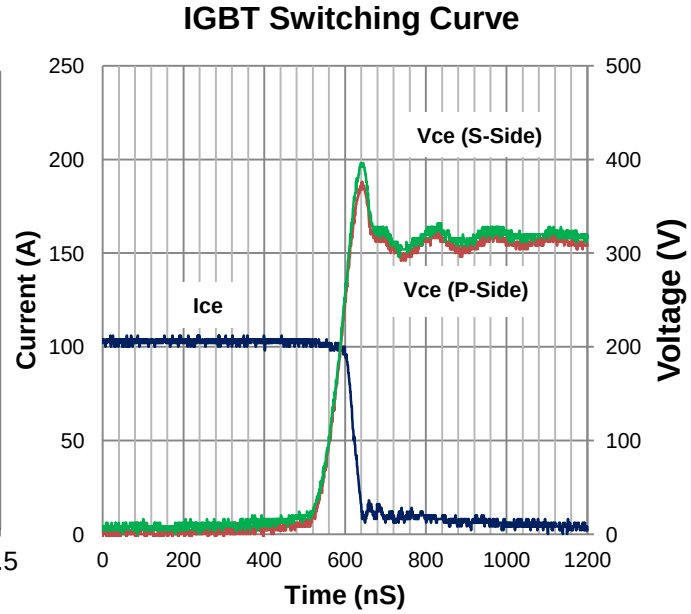
Power Module: Electrical Characterization



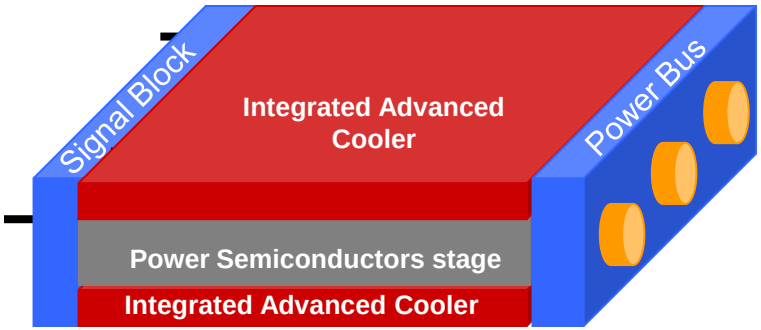


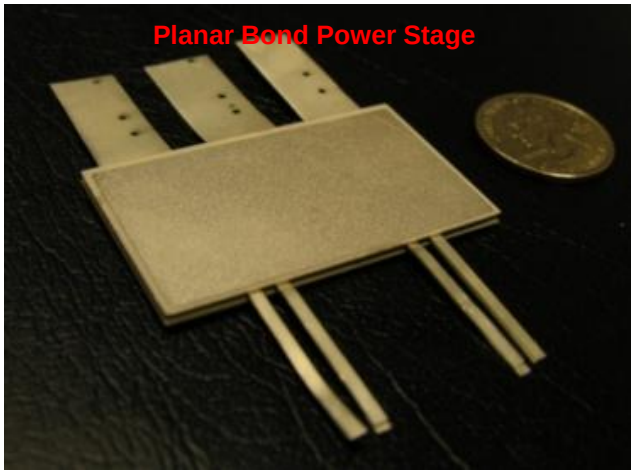


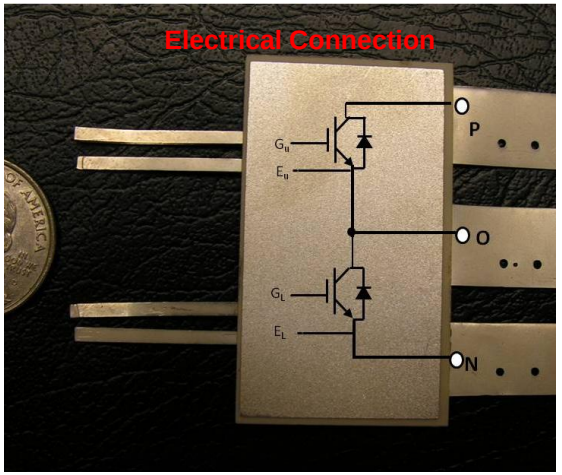




ORNL Planar Bond Automotive Power Module

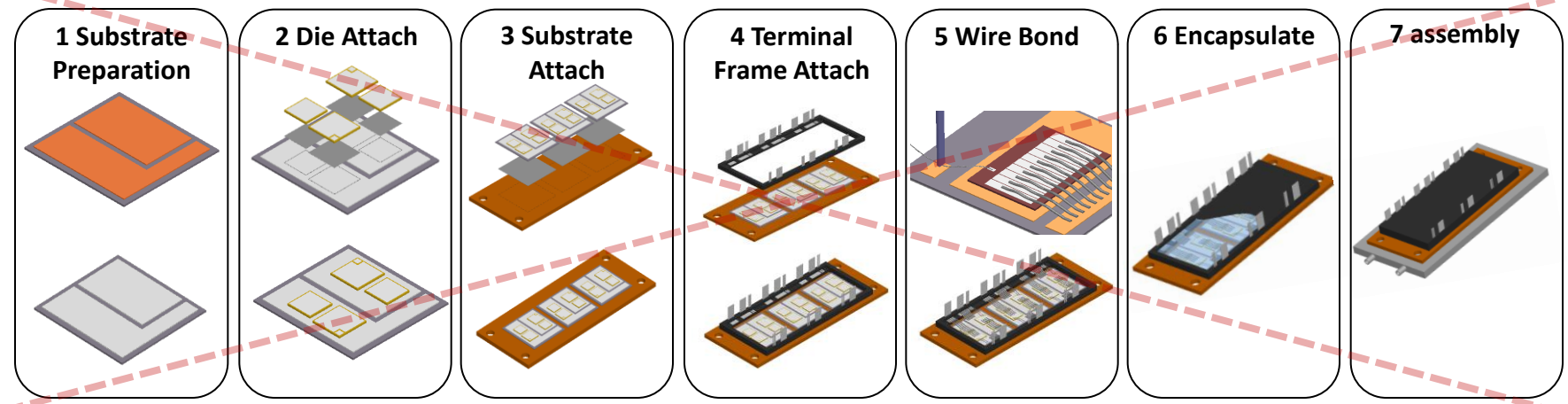






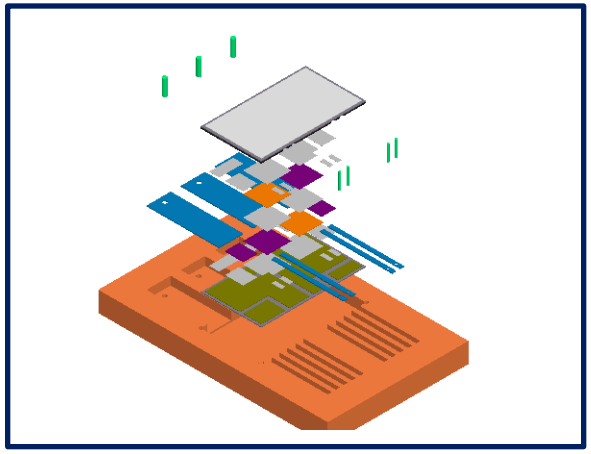
Patent Pending: serial number 61/509312

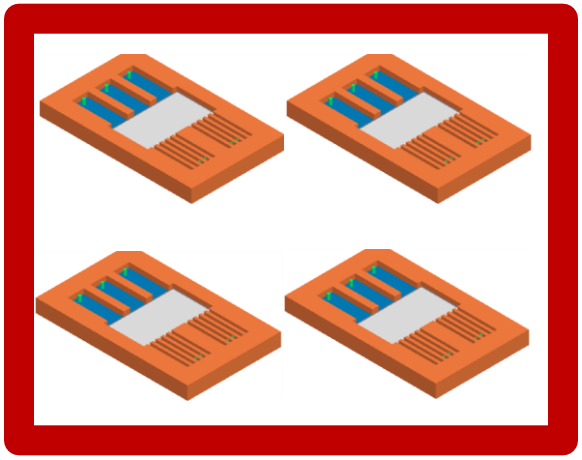
Planar Bond Module Packaging: Manufacturability

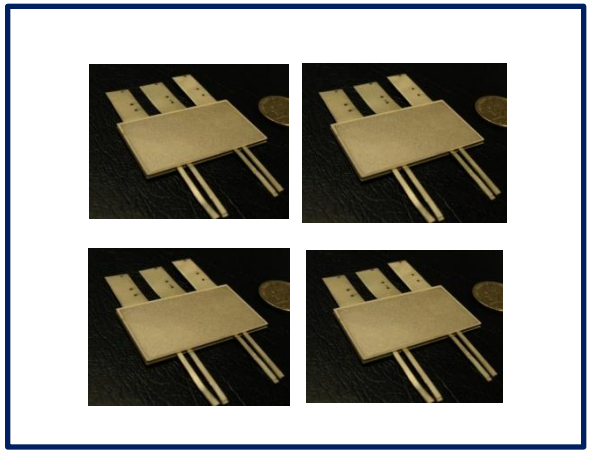


Wire Bond Packaging

Planar_Bond_All

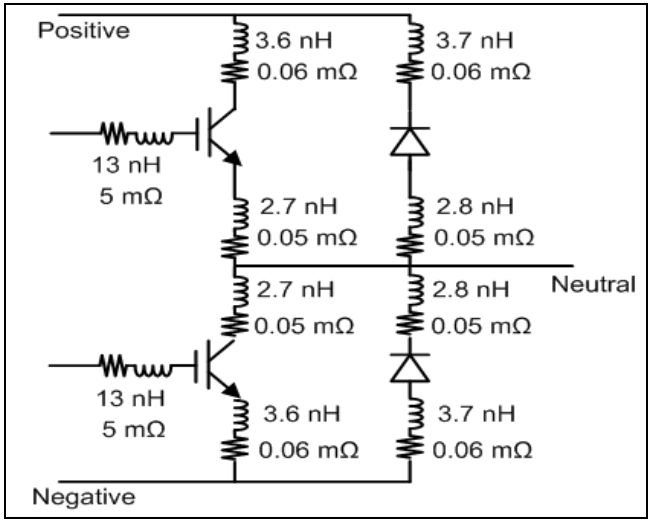


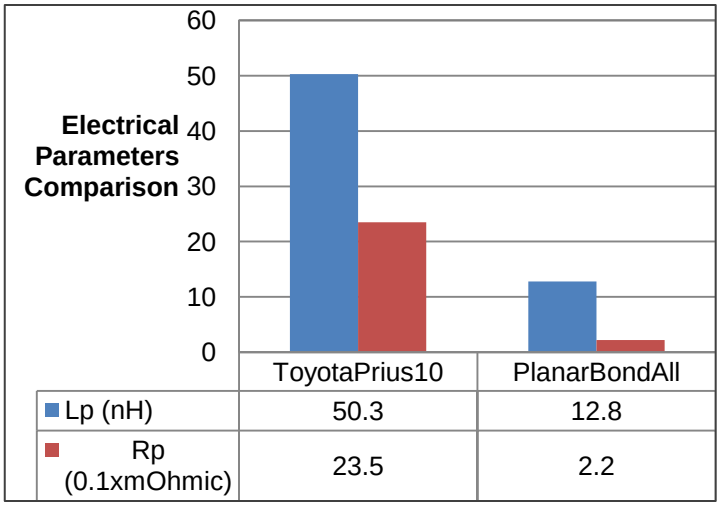


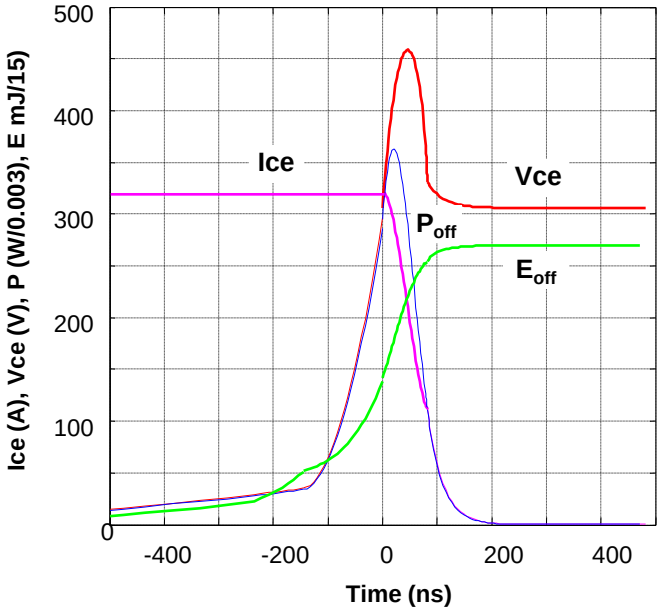


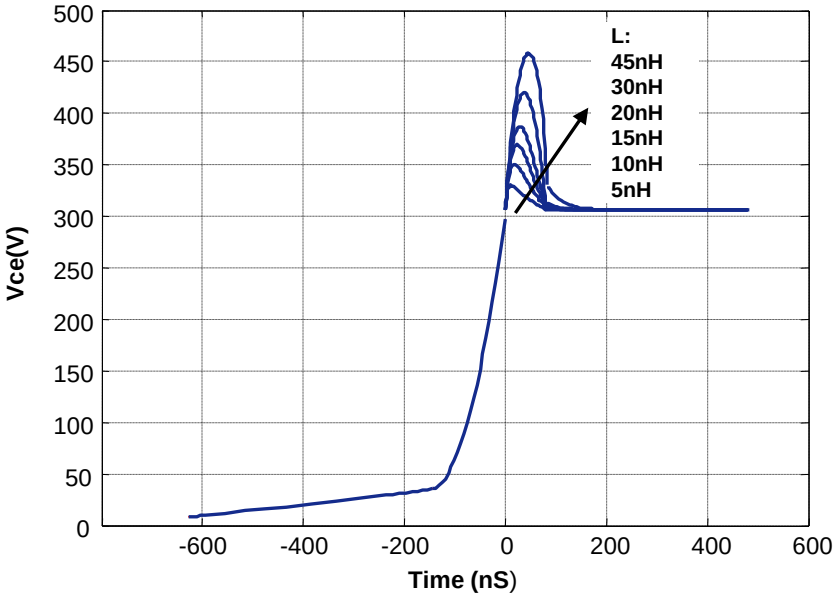
Patent Pending: serial number 61/509312

Planar Bond Module: Electrical Performance Simulation



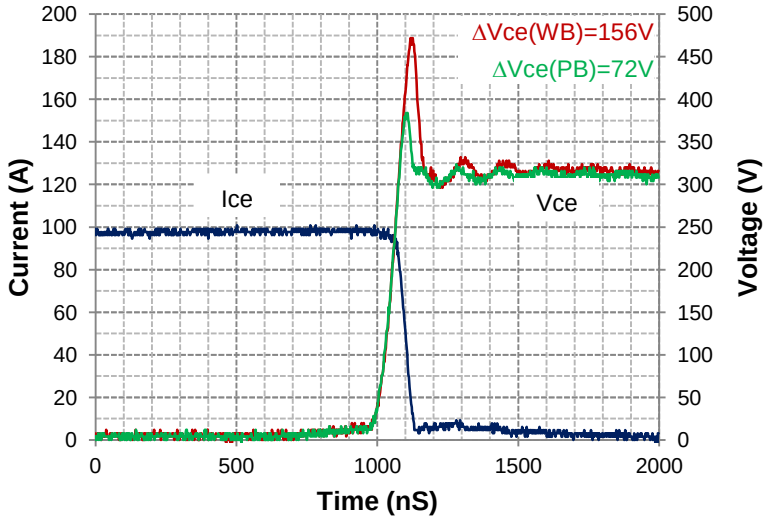


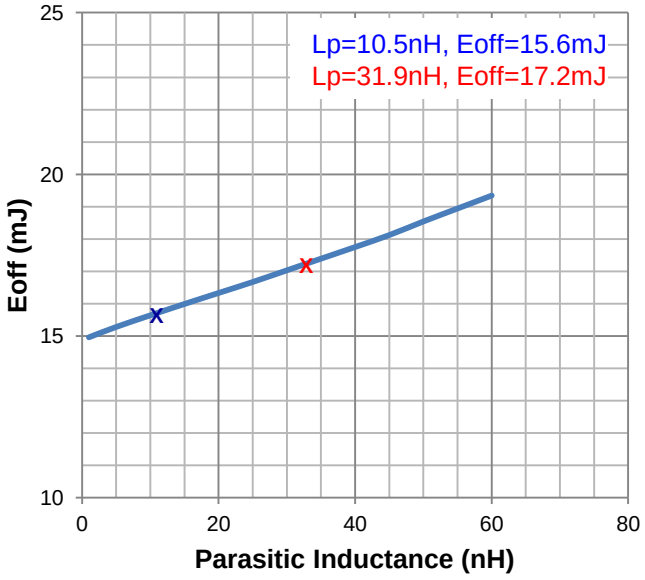


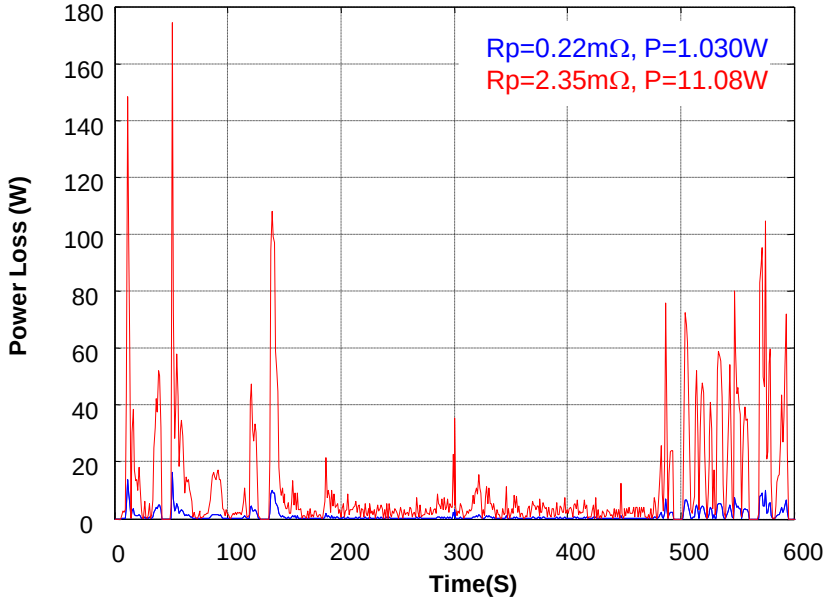


Planar Bond Module: Electrical Experiments and Effects

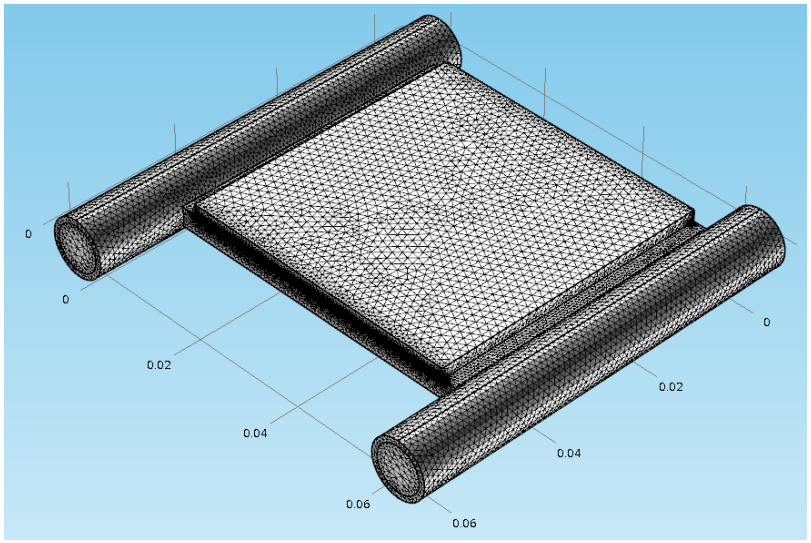
Inductance (nH)	Experimental Value	Calculated Value
Planar Bond_Lower IGBT	10.5	6.3
Wire Bond-Lower IGBT	31.9	23.5

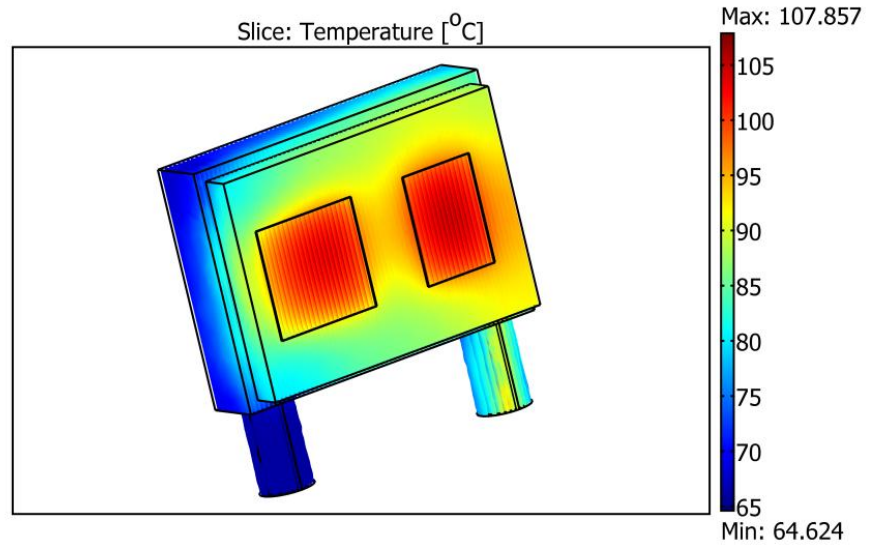






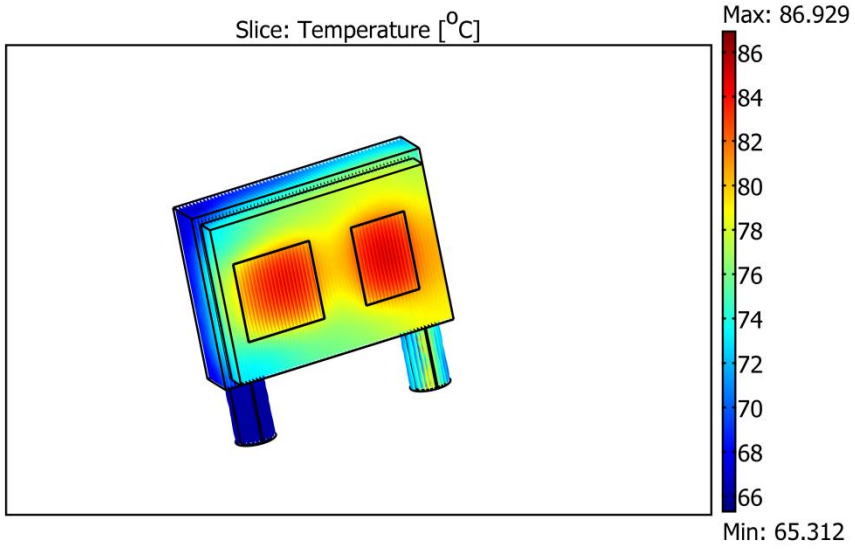
Planar Bond Power Module: Thermal Performance Simulation



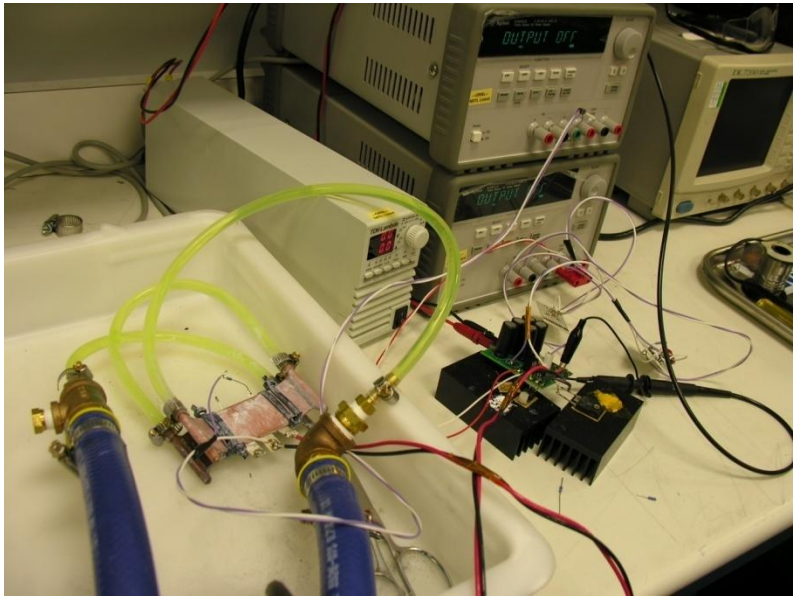


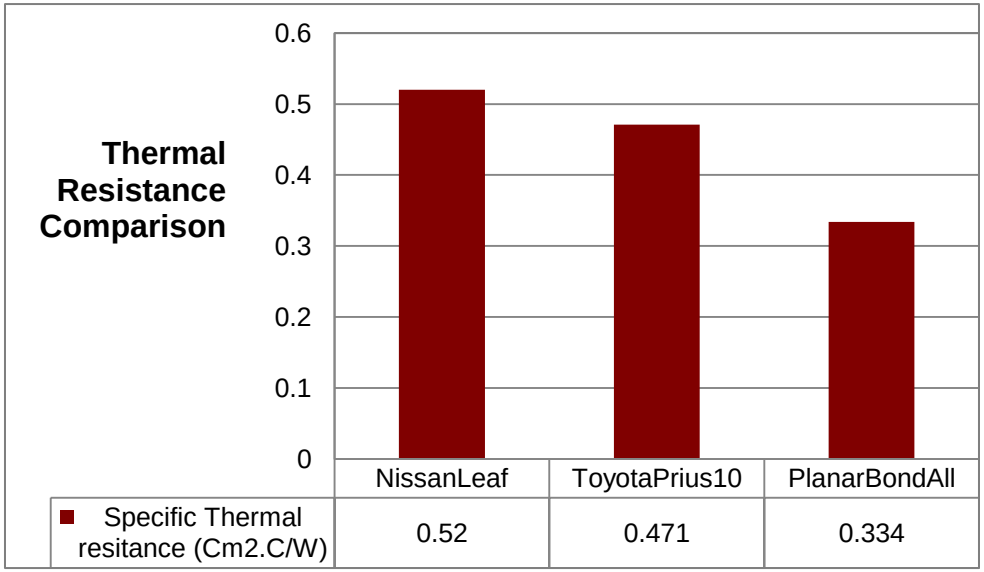
3-D Thermal Model of power module with Cooler

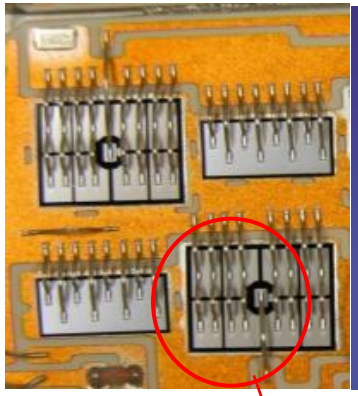
- IGBT, Diode Power loss;
- Coolant flow rate;
- Pressure Drop;
- Coolant inlet temperature;
- Single- or Double-sided cooling.

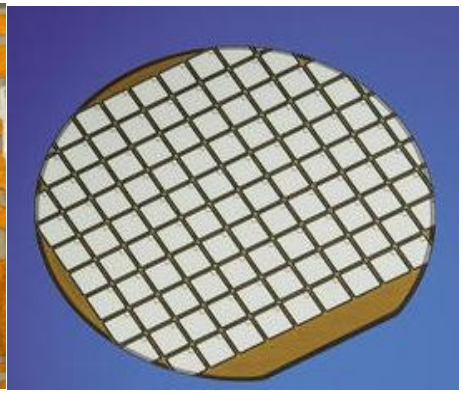


Planar Bond Module: Thermal Performance Measurement Comparison and Effects







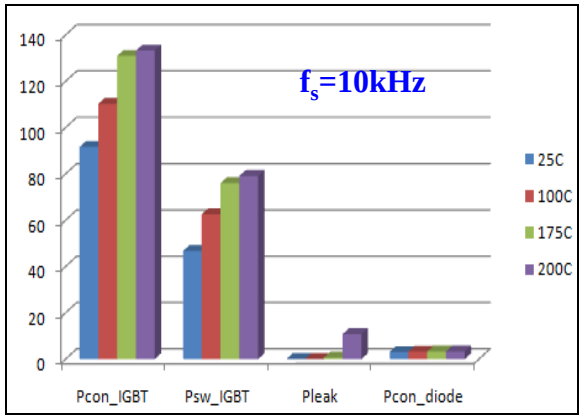


$$\frac{\$}{kW} \propto \frac{S_{Die\ Area}}{P} = \frac{\eta \bullet \theta_{ja,sp}}{(T_j - T_a)}$$

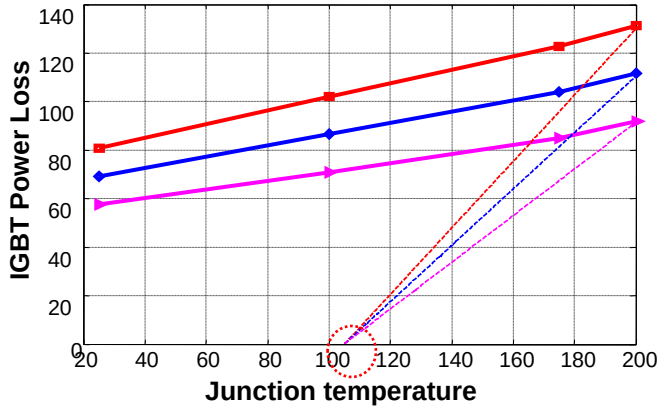
Cost= Die size (S) * $/unit area

Si IGBT Characterization and Evaluation at 200˚C

Losses in one phase leg

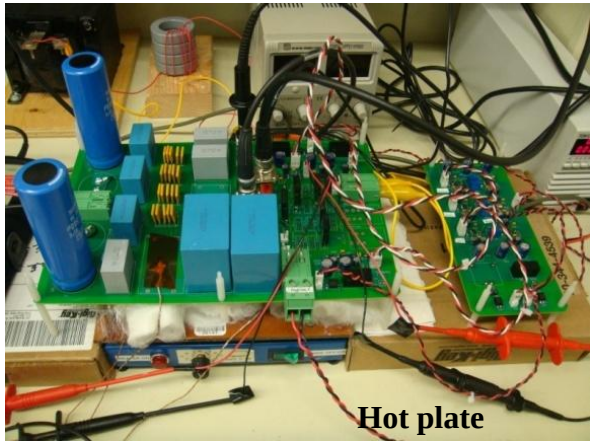


IGBT thermal runaway analysis

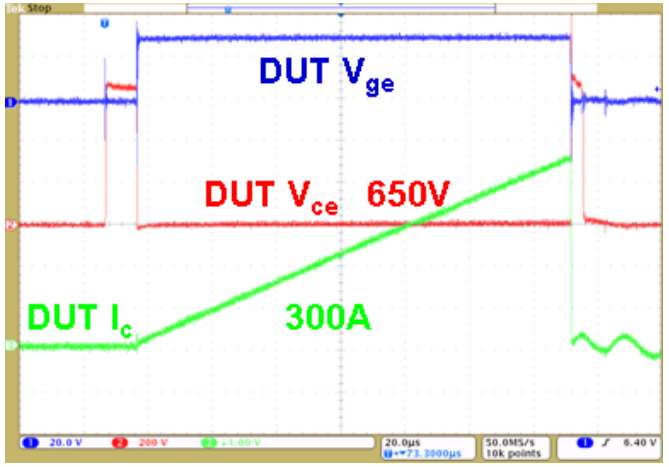


Coolant temperature: 105˚C

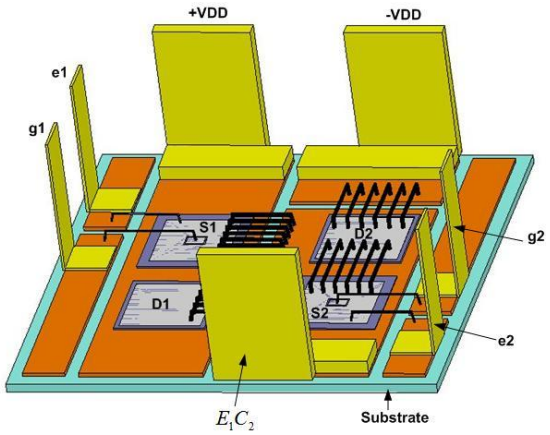
Nondestructive SOA Test



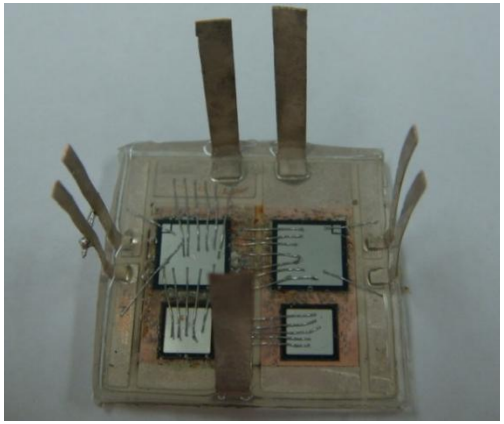
Latch-up current test at 250˚C



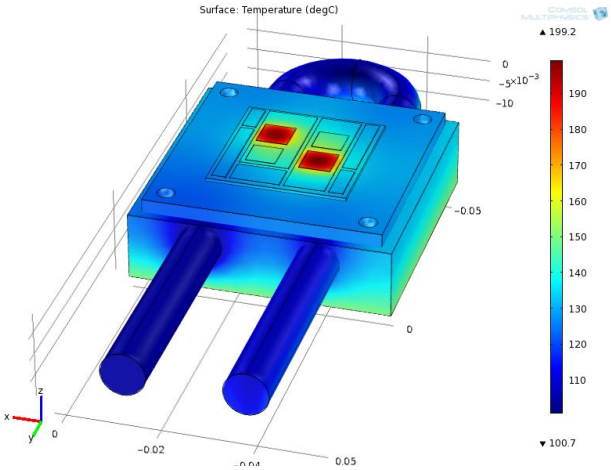
High Temperature Device Packaging Development



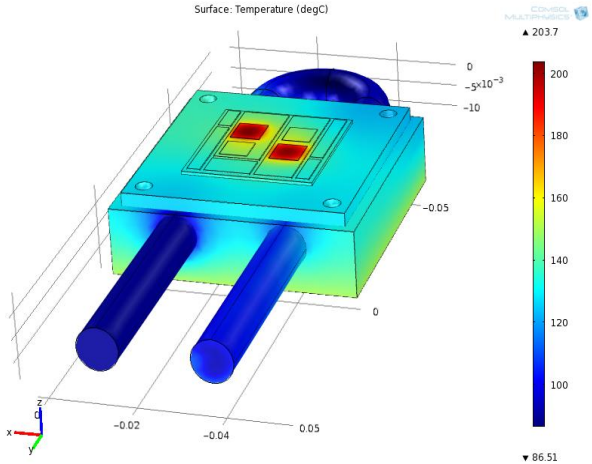
Layout Design



High temperature phase-leg module prototype



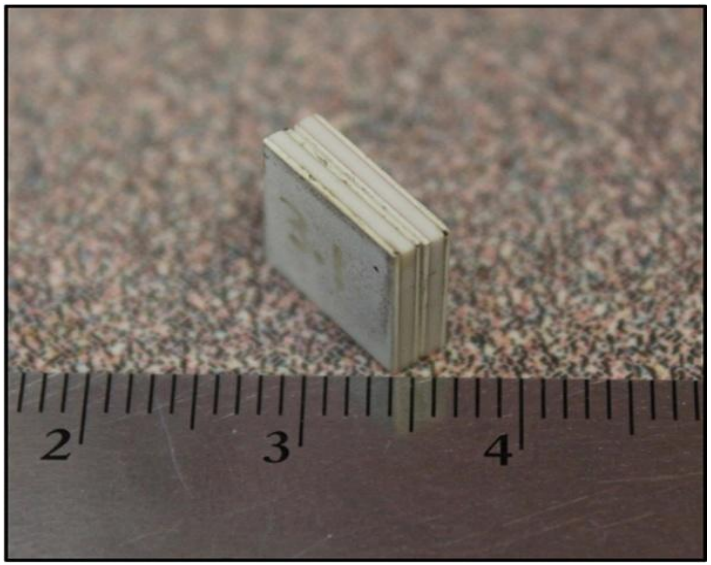
105˚C water/ethylene glycol



90˚C transmission oil

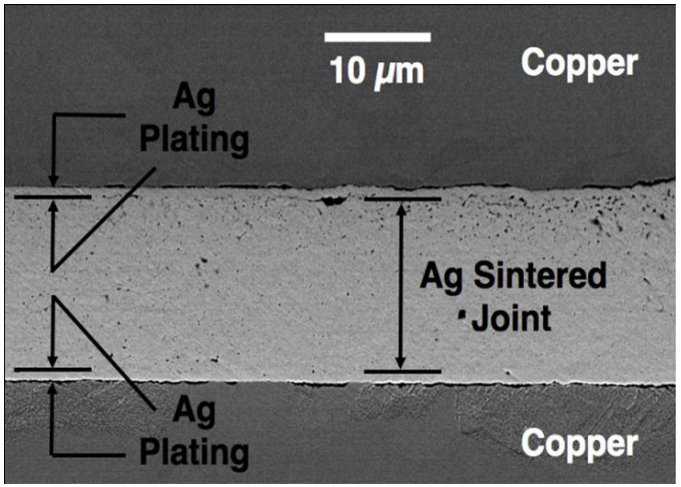
Ag Sintering Development for High Temperature packaging

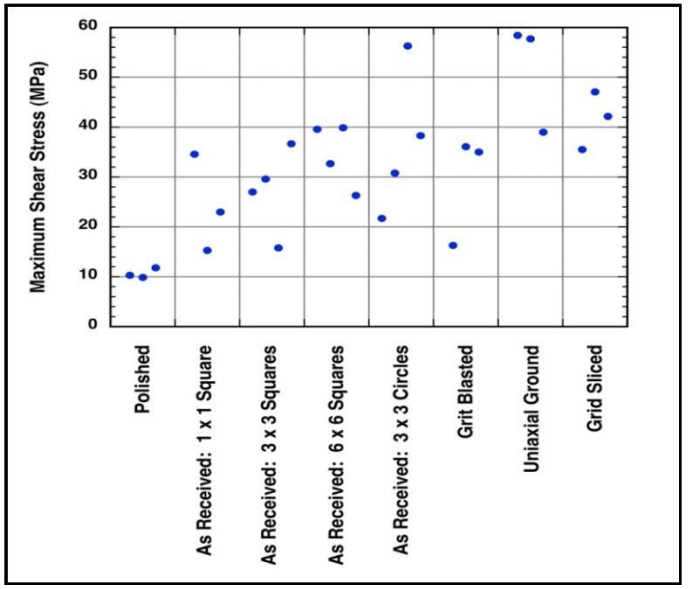
Ag Bonded DBC Substrates



Bond Line View After Tear Down

Cross sectional View of Bond Line





Bond Strength vs. Topography

Summary and Future Work

- **Developed power module packaging technologies, focusing on improvements in performance, reliability and cost effectiveness through structure optimization, material and processing developments.**
- **A planar power module prototype features low electric parasitics and thermal resistance. Additionally, the package allows for ease of fabrication and low manufacturing costs.**
- **Further research into thermo-mechanical properties needed to assure the reliability of power electronics in automotive harsh environments.**
- **Develop advanced structure/material/process schemes for high temperature and high frequency operation of Si and wideband gap (SiC, GaN) power devices to advance HEV and EV technologies.**

Acknowledgement

The automotive power electronics packaging work has been primarily supported by DOE under Vehicle Technologies Program. The authors would also like to thank their colleagues, Puqi Ning, Andrew A. Wereszczak, Randy Wiles, all with ORNL for the contribution to this presentation

Thanks And Questions?