Cross-Industry Reliability: Automotive Power Module Perspective

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2013 PV System Symposium

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Outline

- Introduction
  - ***Power Electronics in Electric Drive Vehicles***
  - ***Automotive Power Electronics Module Operation***
  - ***Automotive Power Module Packaging***
- High Reliability Power Module Packaging
  - ***Packaging Materials***
  - ***Structure Optimization***
  - ***Process Innovation***
- Emerging Automotive Power Module Packaging
  - ***200℃ Si Power Module***
  - ***Planar-Bond -All (PBA) Power Module***
  - ***Advanced All-SiC power module***
- Summary

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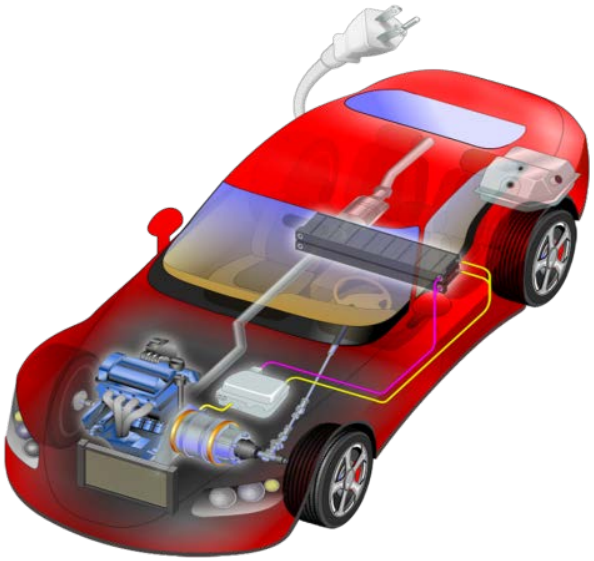
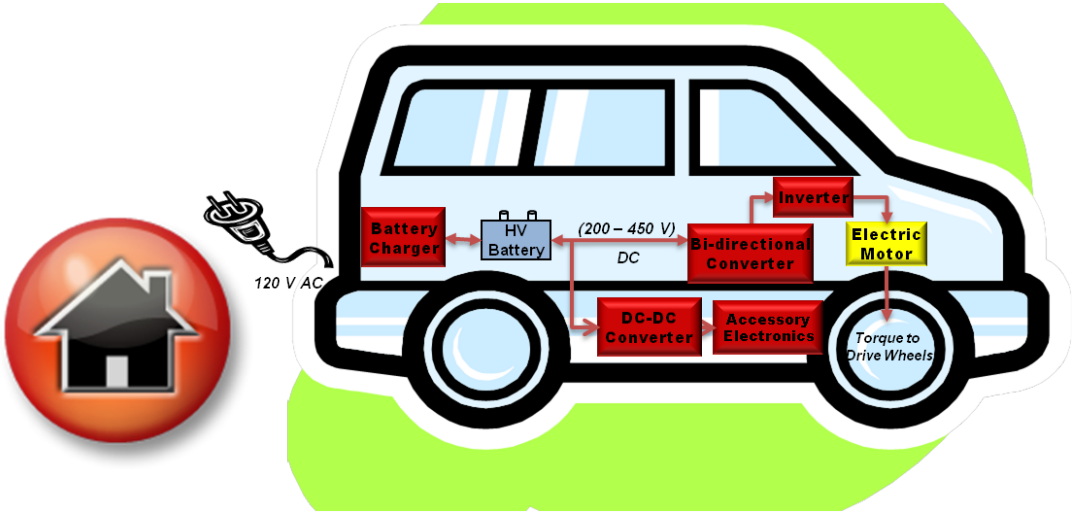
Power Electronics in xEVs



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



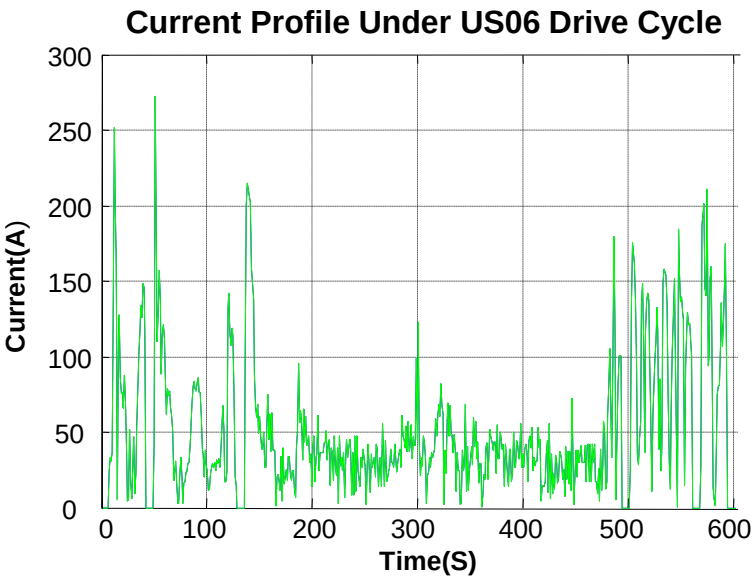
http://www.motortrend.com/oftheyear/car/1201_2012_motor_trend_car_of_the_year_contenders_and_finalists/photo_255.html

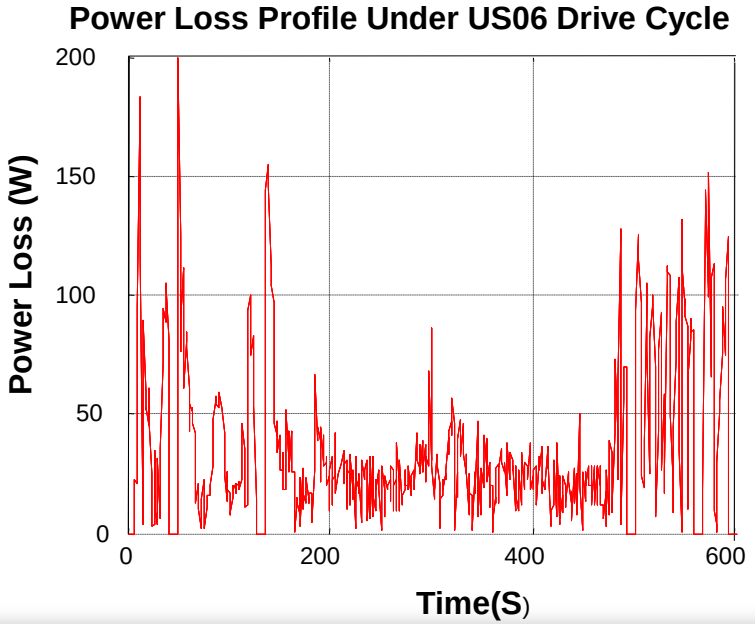
Power Electronics Modules in xEVs

Typical Traction Drive Requirements: 55 kW peak power for 18 sec;
30 kW continuous power;
15-year life

Temperature / Environment

Ambient air: -40°C to 135°C
Coolant water: -40°C to 105°C
Junction: -40°C to 175°C
Vibration: 10g
Shock: 50g





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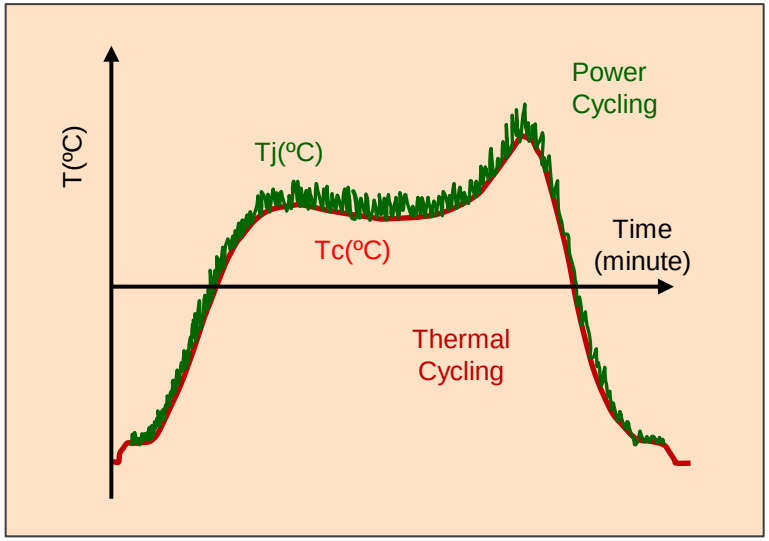
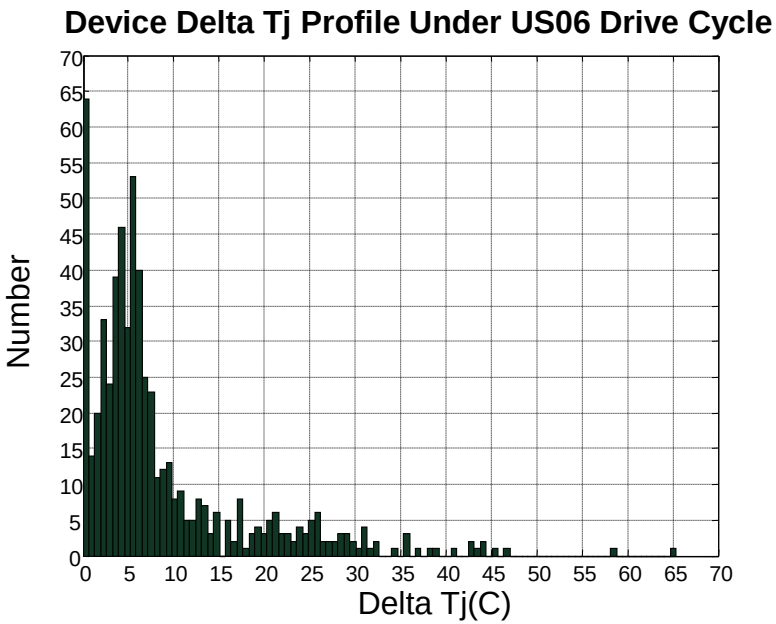
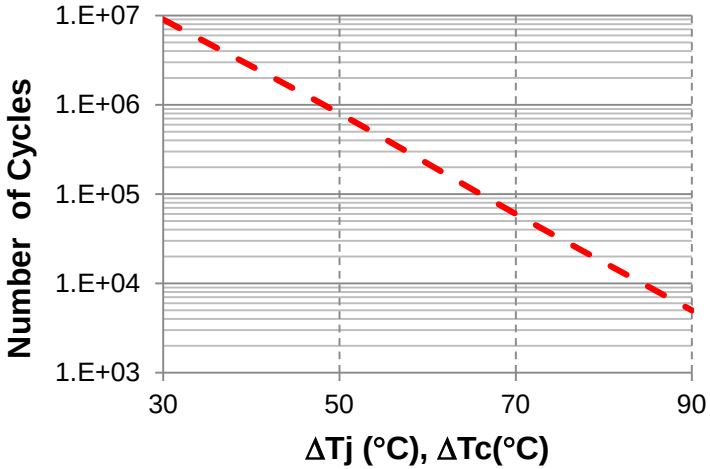
Automotive Power Module Reliability







$$LiftimeConsumption = \sum_{i=1}^{Max} \frac{N_i(\Delta T_{j_i})}{N_f(\Delta T_j)}$$

- **Power Derating**
- **Advanced Semiconductors and Advanced Packaging**

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Comprehensive Evaluation

Semiconductor Characterization

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

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

Thermal characterization

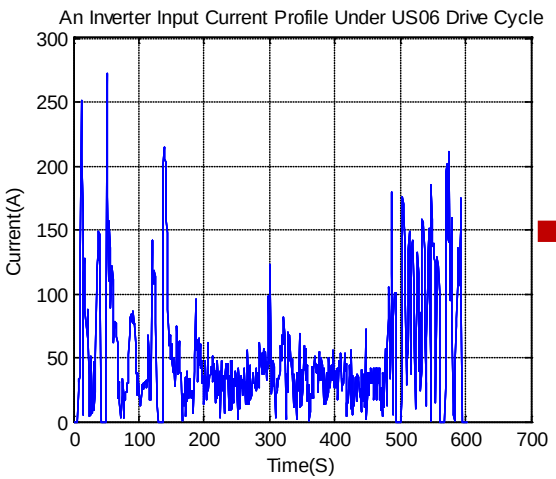
$$\theta_{ja} = \alpha * S^{-\beta}$$

Electrical Characterization

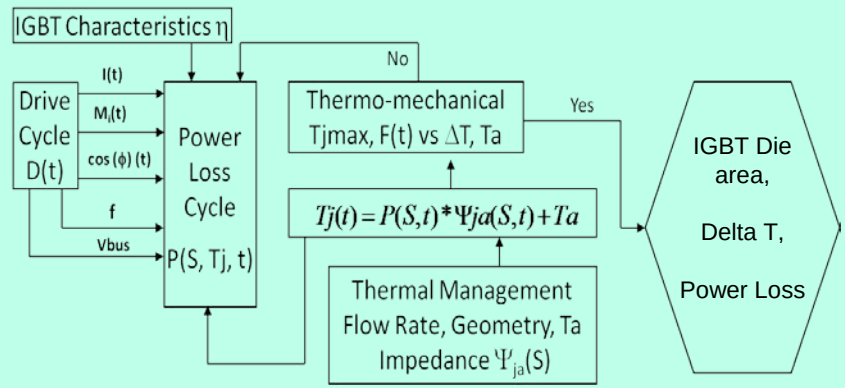
Lp, Rp

Reliability Characterization

$$N_f = \alpha \cdot (\frac{1}{Tj - Ta})^{\beta} \cdot \exp(E_a / kT_m)$$



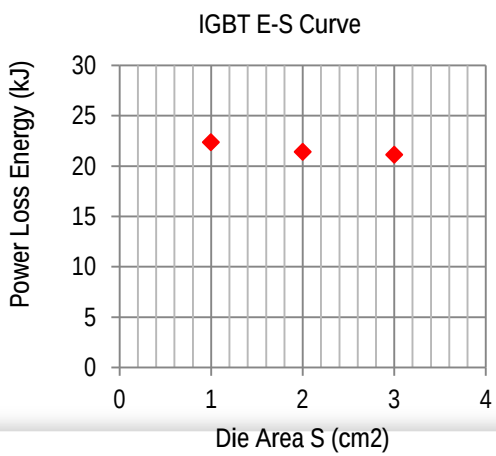
ORNL Power Module Evaluation Program

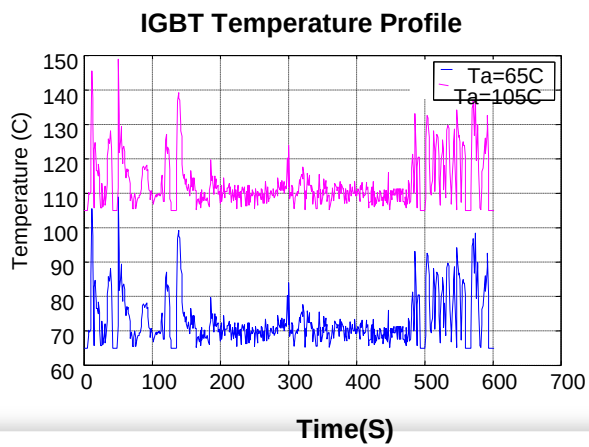


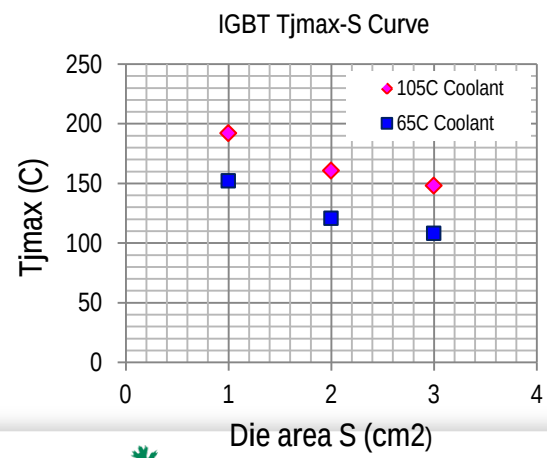
Cost

Reliability

Efficiency







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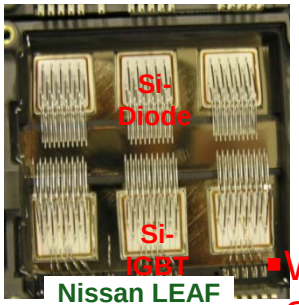
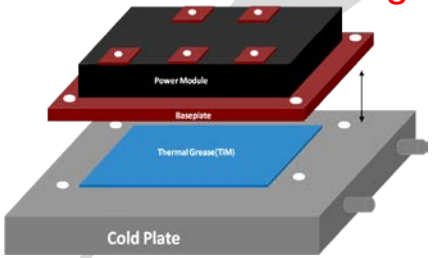
Si Module Packaging Status and Trend

$$\frac{\$}{kW} \propto \frac{S_{Die\,Area}}{P} = \frac{(1-\eta)\cdot\theta_{ja,sp}}{(T_j - T_a)}$$

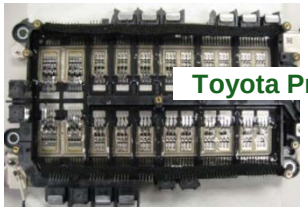


Nissan LEAF

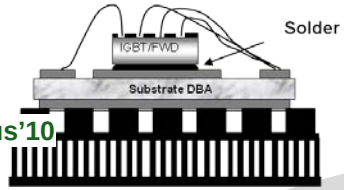
Gen_I
- Wire Bond
- Single Side Interfacial Cooling



Inverter Assembly

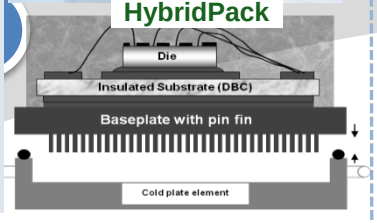


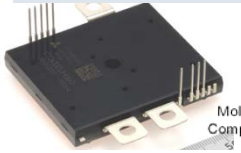
Toyota Prius'10



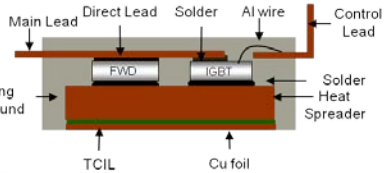
Gen_II
- Planar Bond
- Integrated Cooling
- Reliability Enhancement

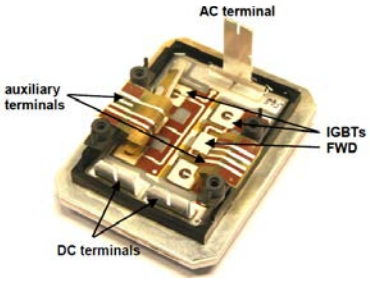
Infineon HybridPack



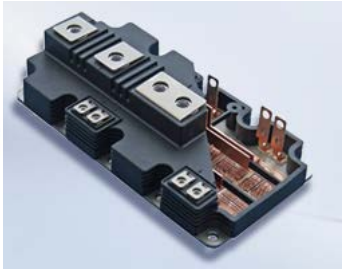


Mitsubishi TPM





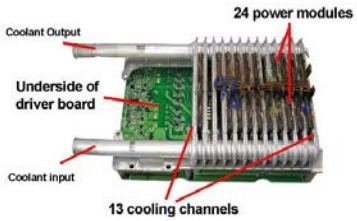
Semikron SKiN



Infineon .XT

Gen_III
- Dual Planar Bond
- Double Sided Cooling
- Integrated Double Sided Cooling

Toyota LS600



Hitachi DCPM

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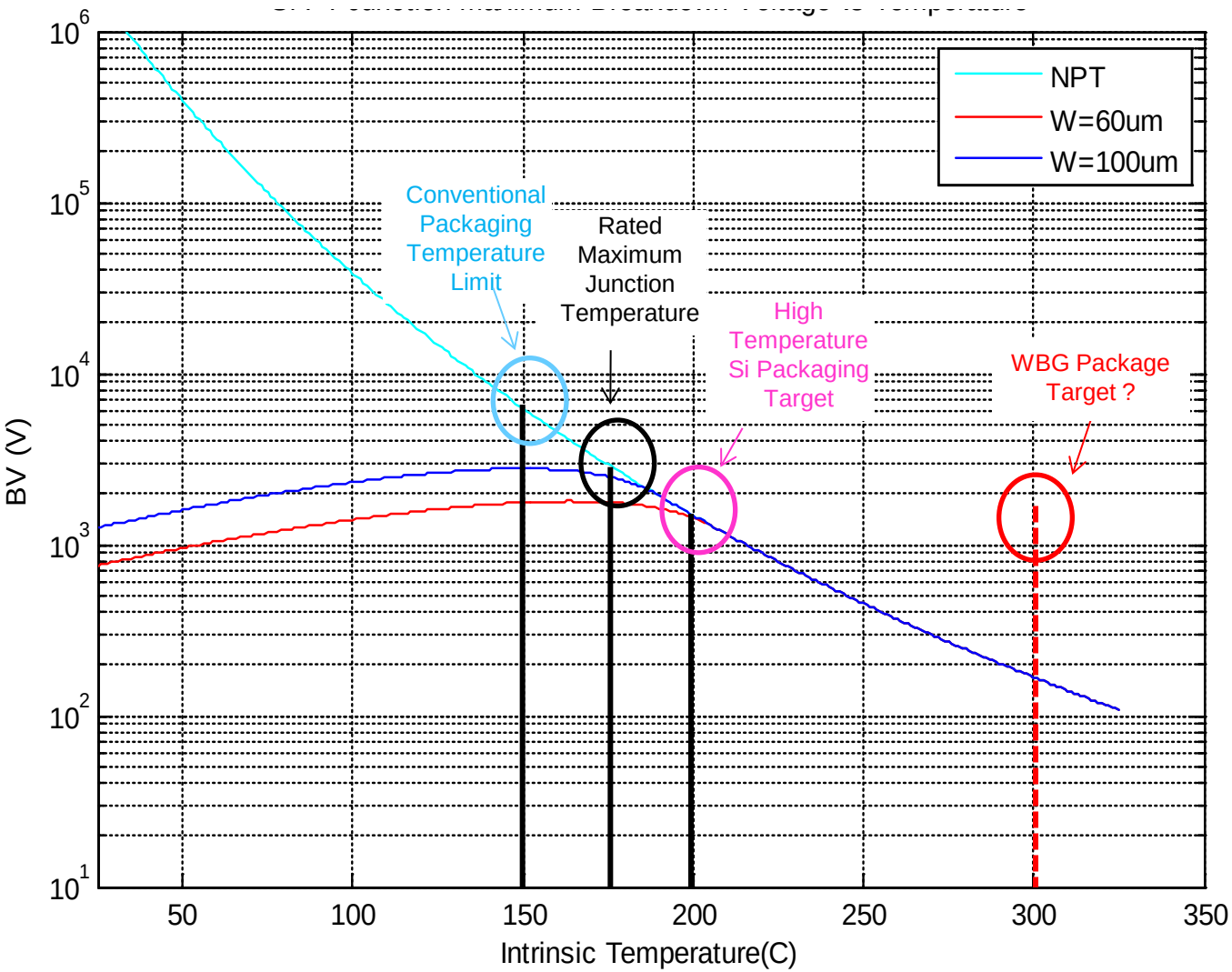
Operation Temperature of Power Module



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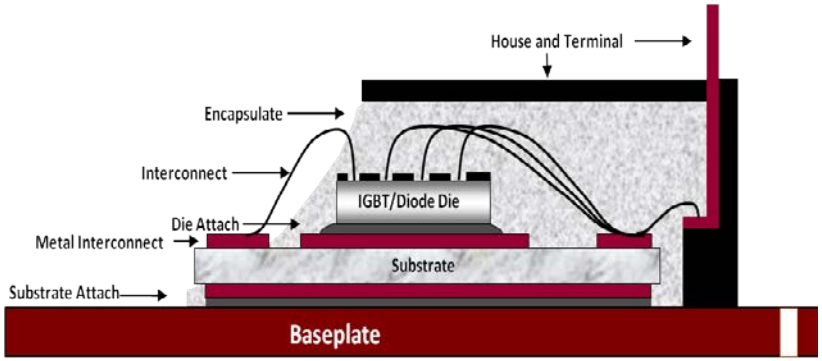
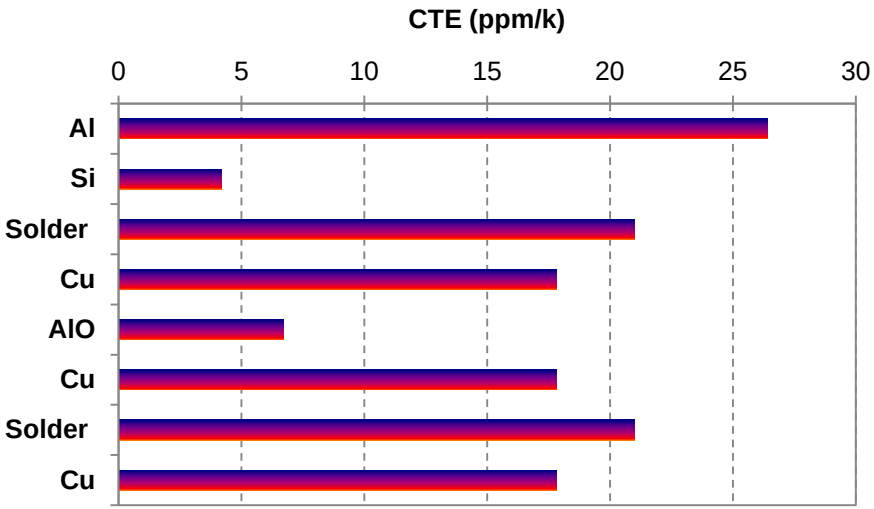
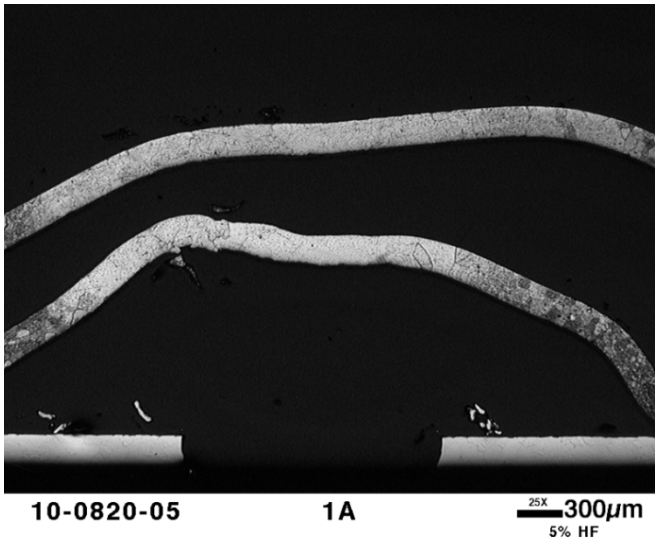
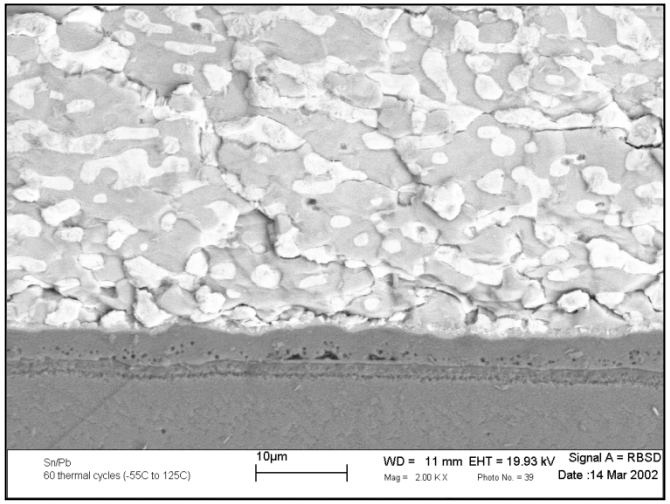
Failure Mechanism: Thermal Expansion and Fatigue







http://www.ornl.gov/sci/propulsionmaterials/pdfs/FY10_Qtr3.pdf



Dimos Katsis, Ph D dissertation, Virginia Tech

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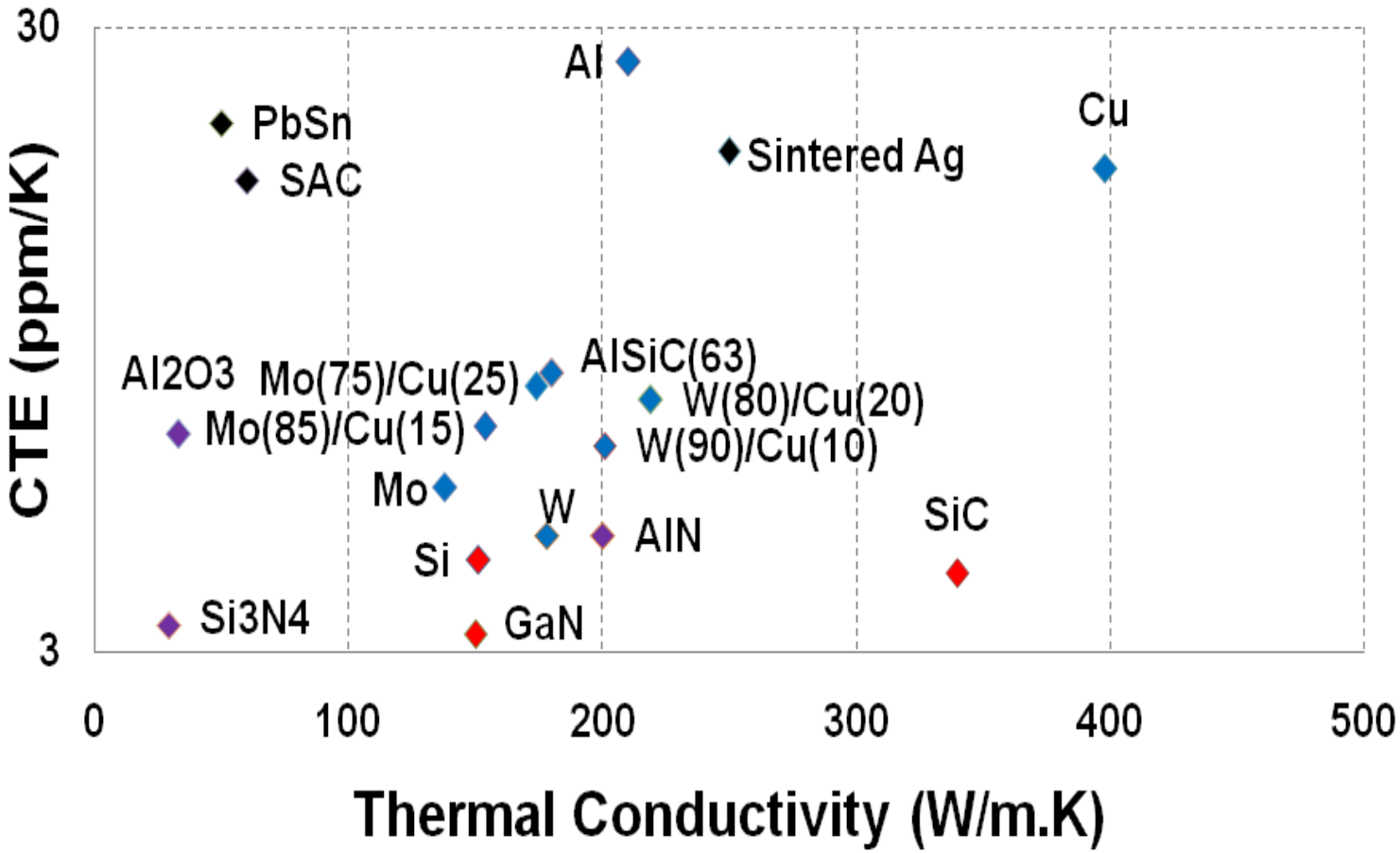
Power Module Packaging Materials



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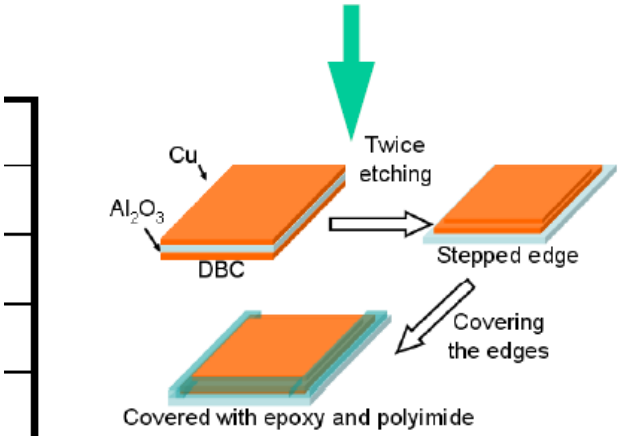
High Reliability Packaging: Structure Optimization

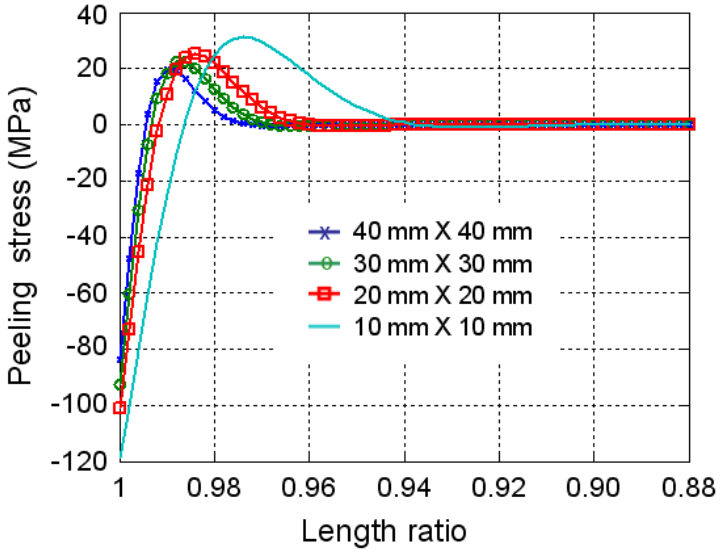
Original DBC failed after 20 cycles

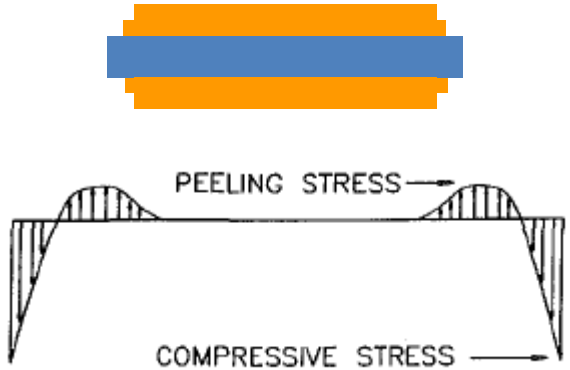


Failed after 1300 cycles

Lifetime **70X**

12





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

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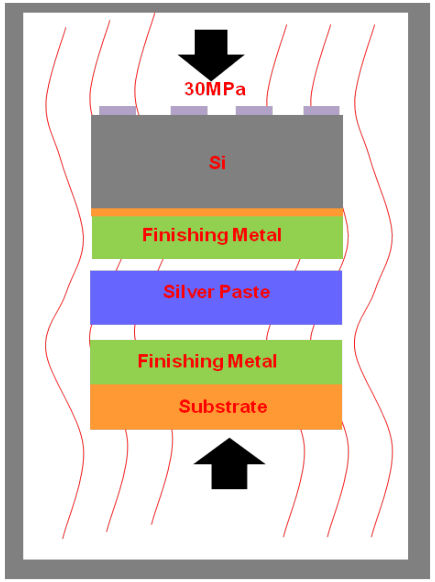
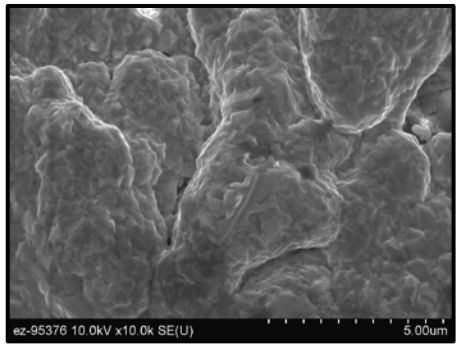
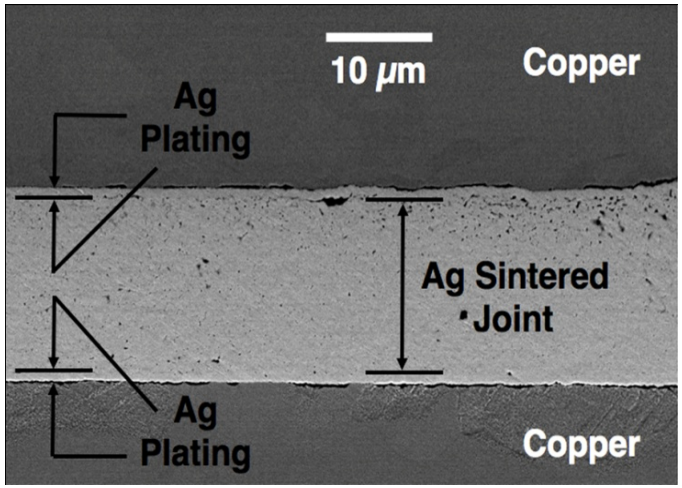
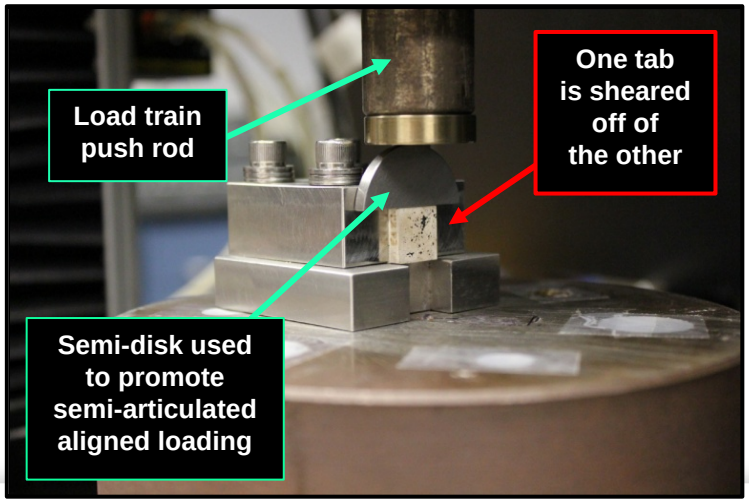
High Reliability Packaging: Ag Sintering Die Attach

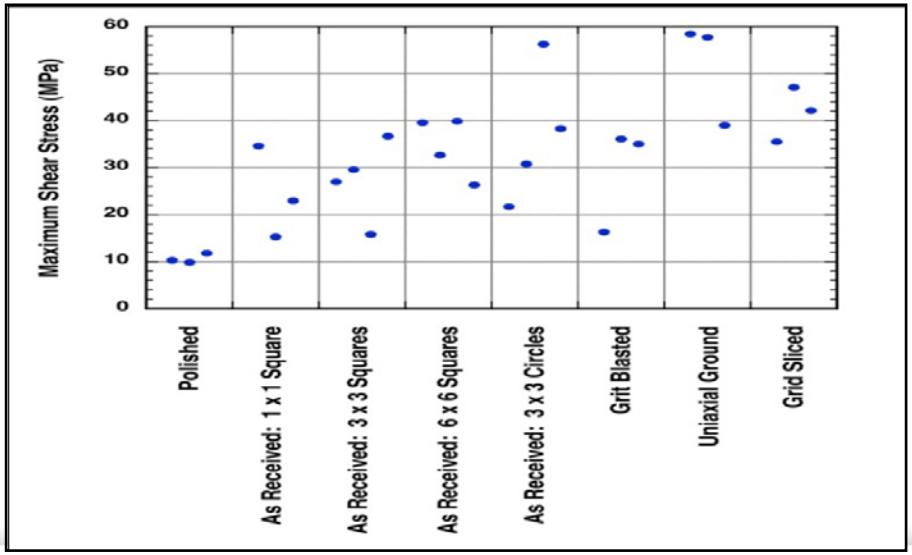








Bond Strength vs. Topography



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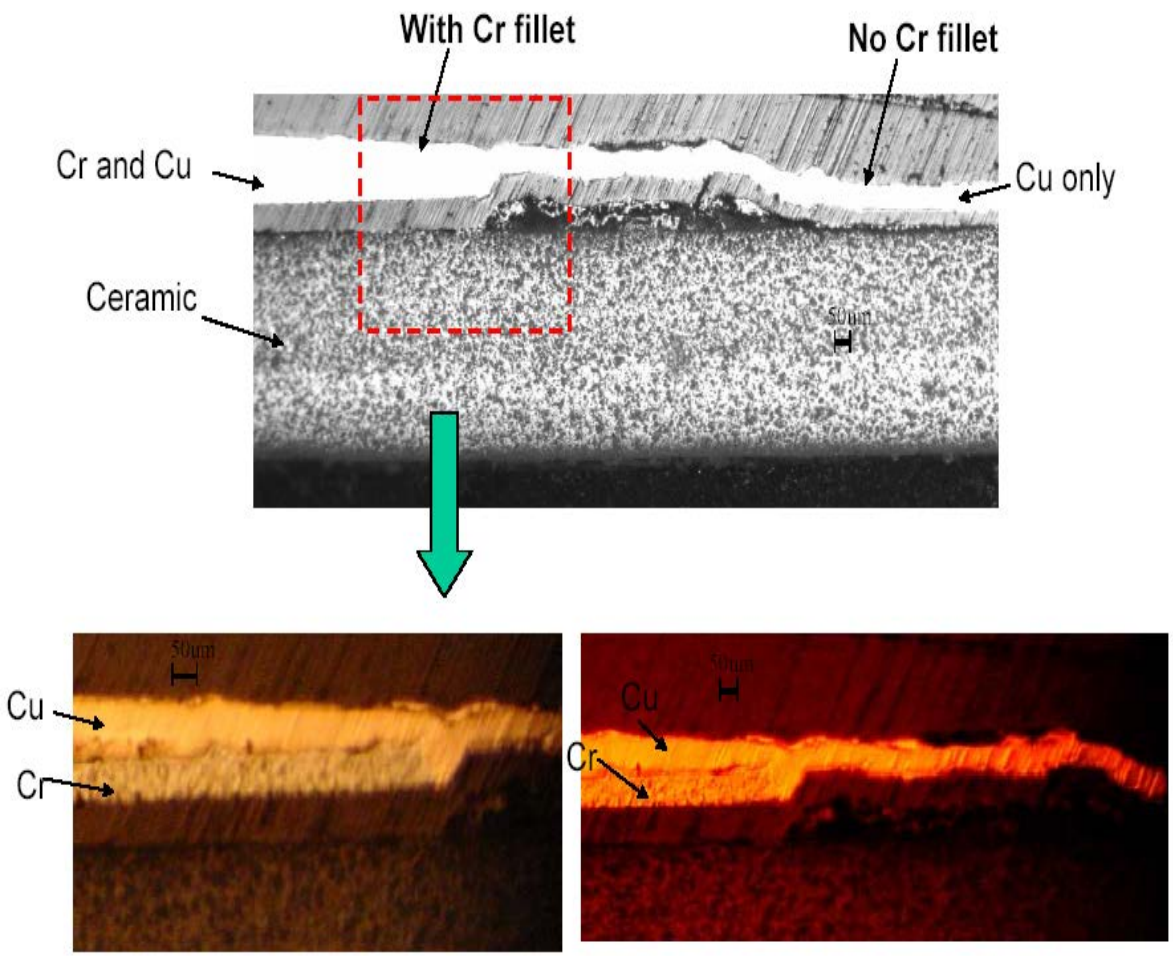
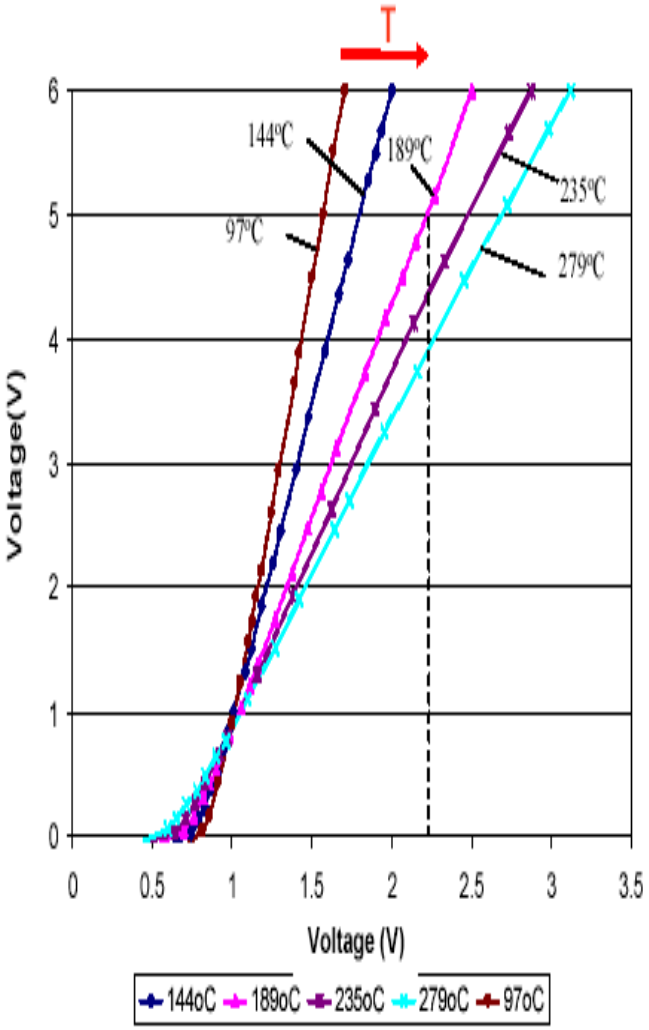
Complex Metallization Interconnection





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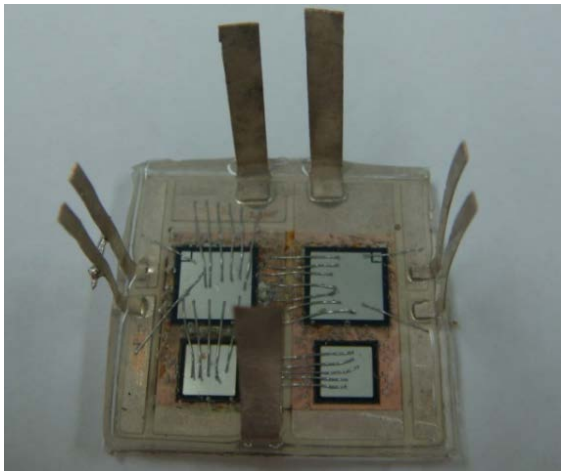
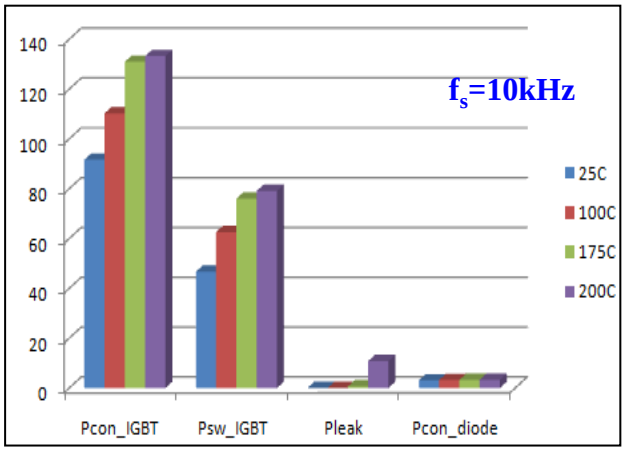
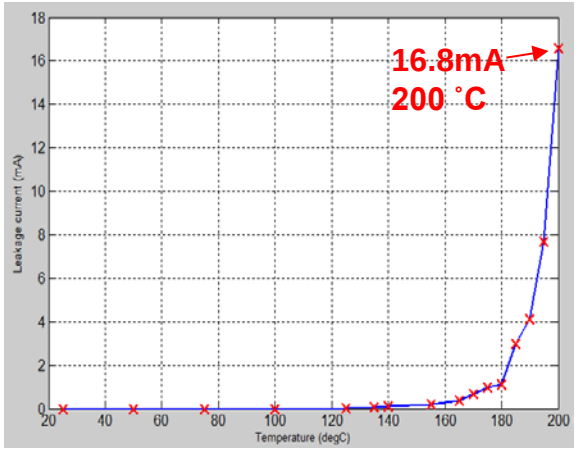
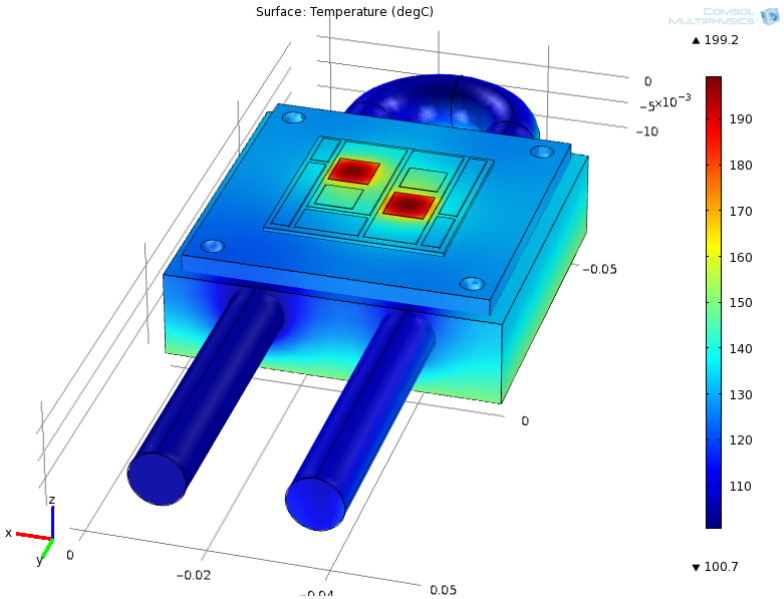
200˚C Si IGBT Power Module

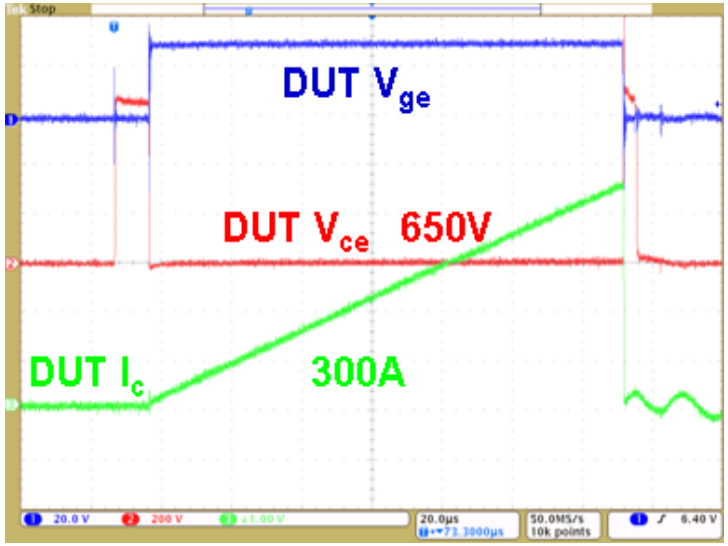








105˚C water/ethylene glycol



Latch-up current test at 250˚C

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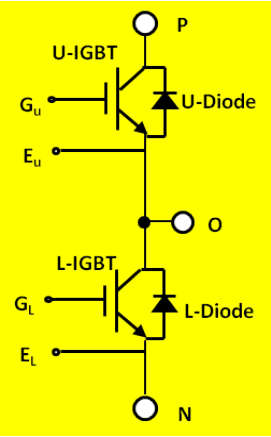
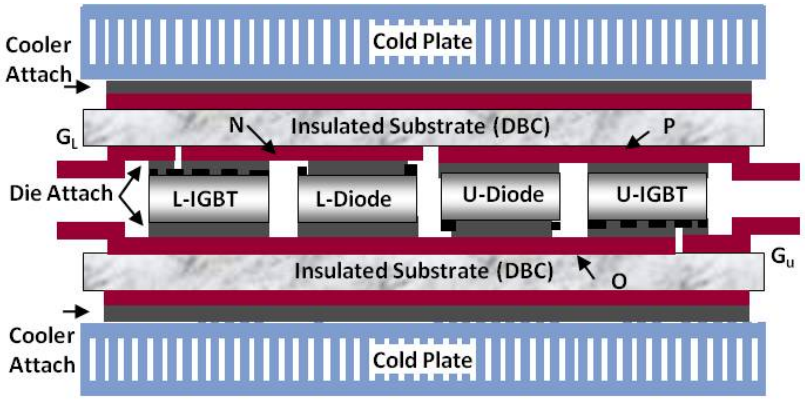
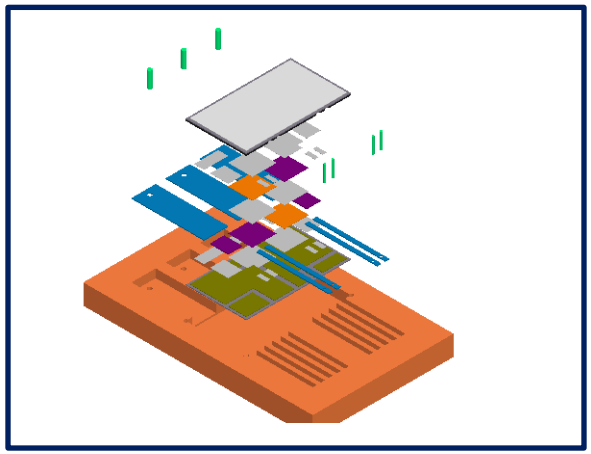
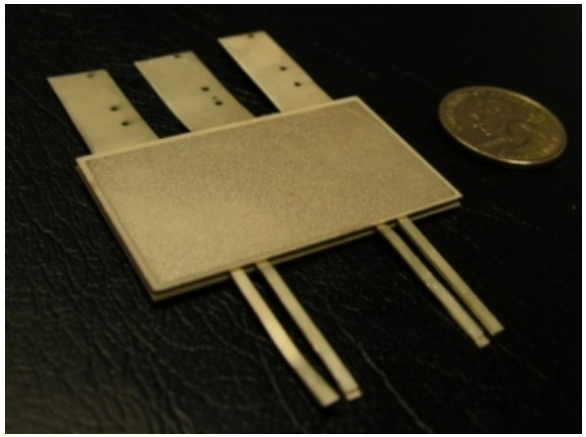
New Concept: Planar Bond All Integrated Power Module

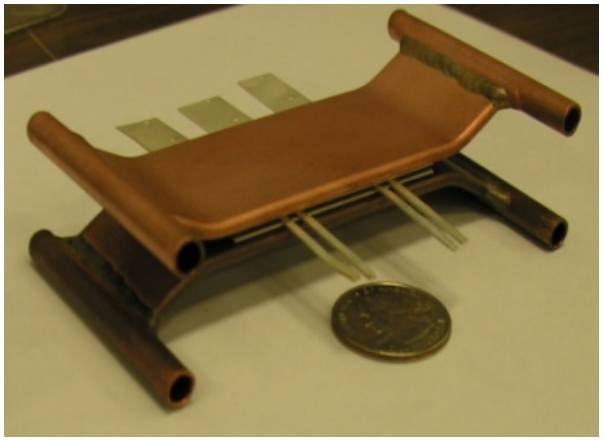




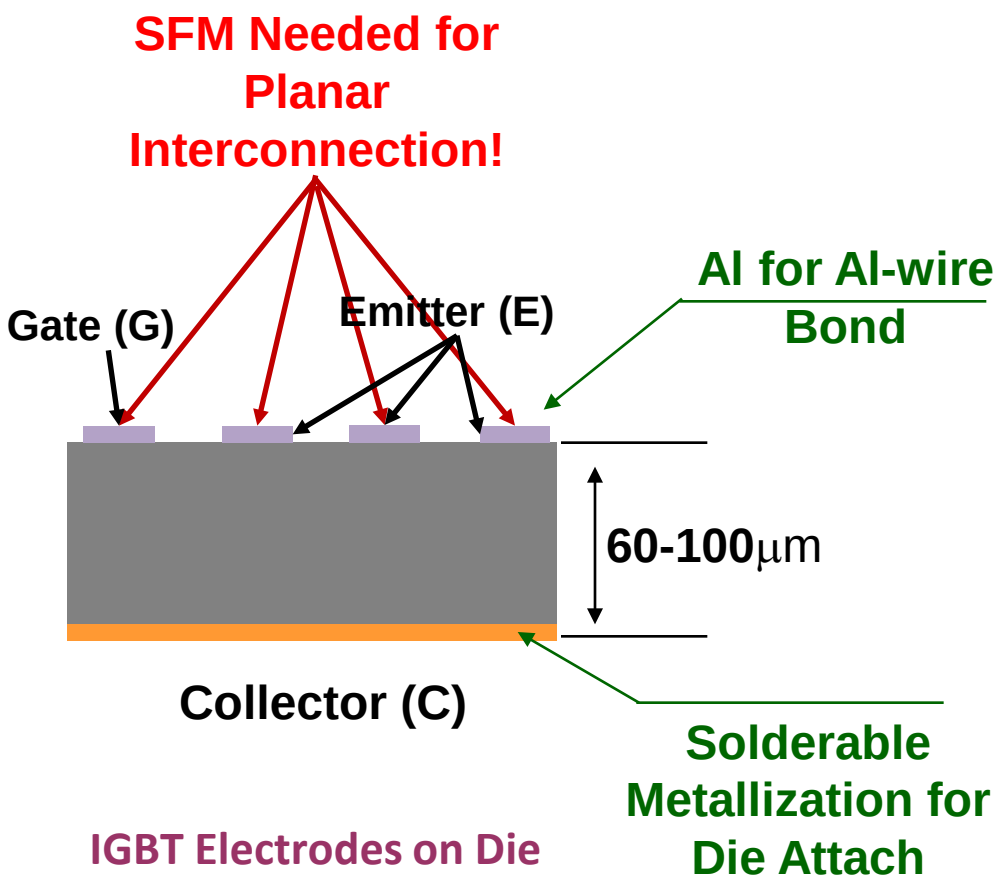
- ***3-D, Planar Power Interconnection***
- ***Integrated, Double Sided Cooling***
- ***Symmetrically Mechanical Structure***
- ***Simplified Manufacture***



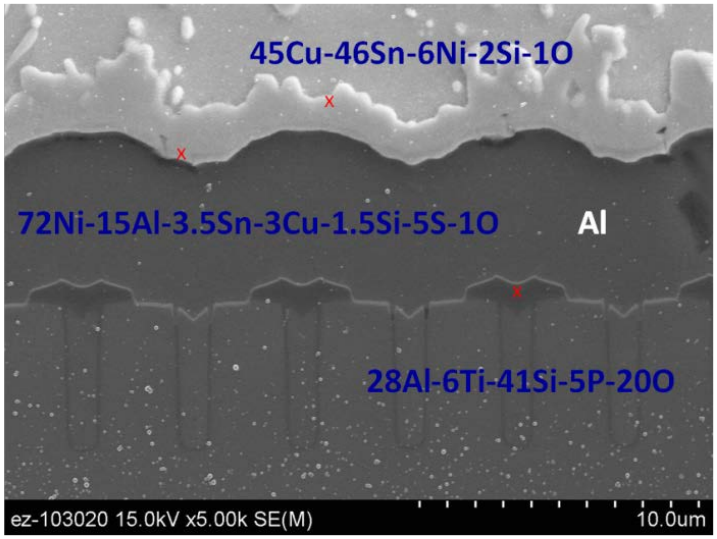




Solderable Front Metallization



IGBT Electrodes on Die



Microstructure View of a SFM IGBT Package

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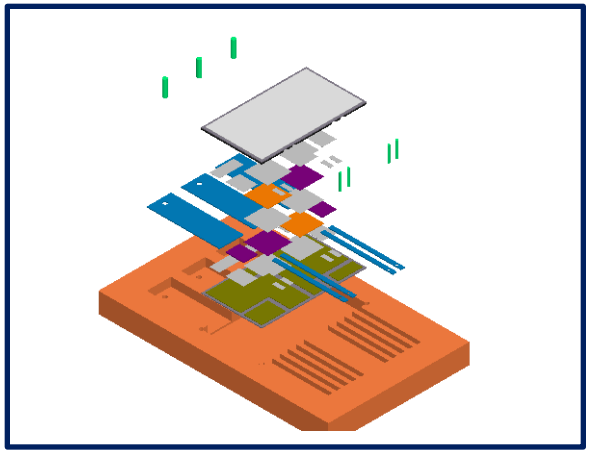
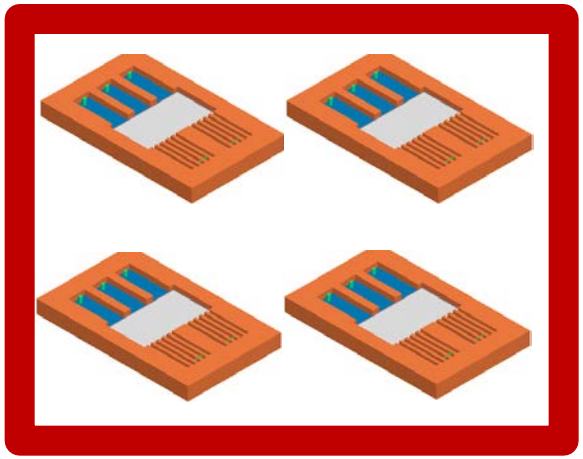
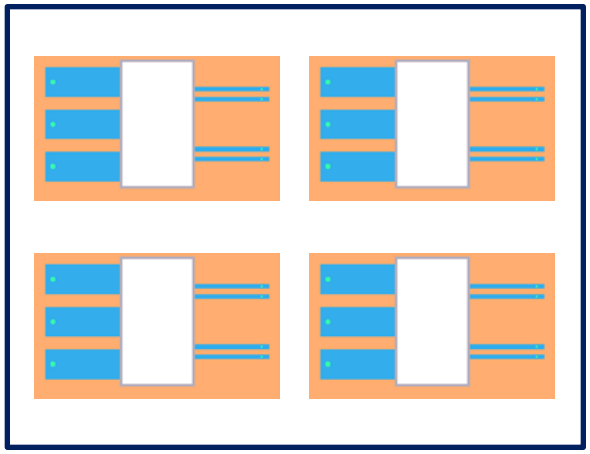
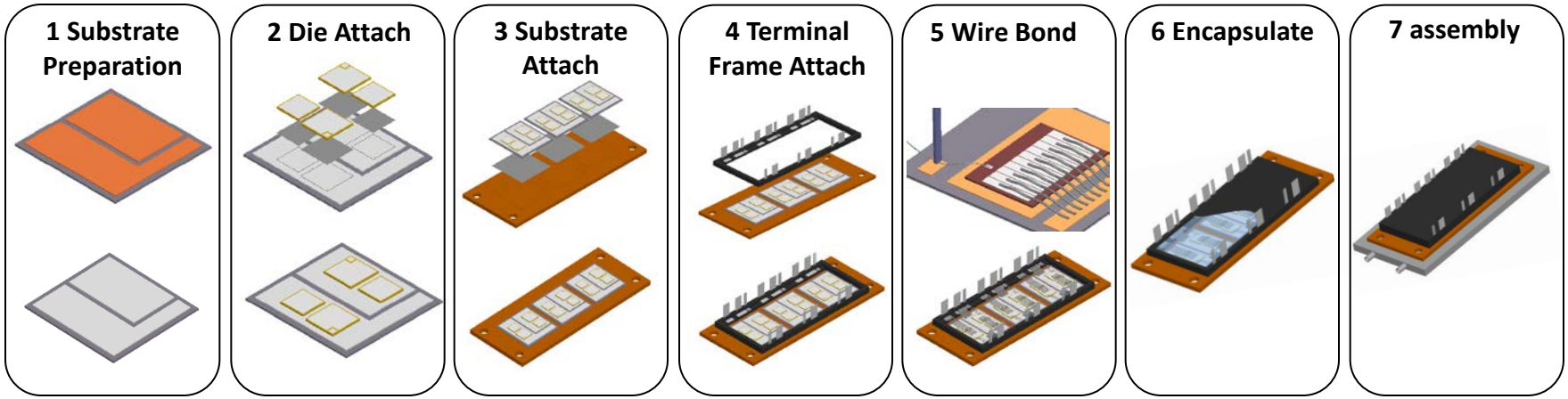
Develop New Packaging Process Technology

Planar_Bond_All*









Wire Bond Packaging

***Patent Pending: US2013/0020694**

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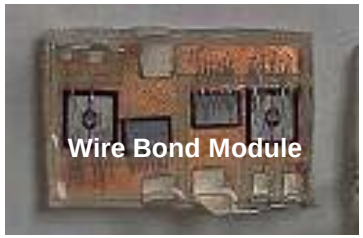
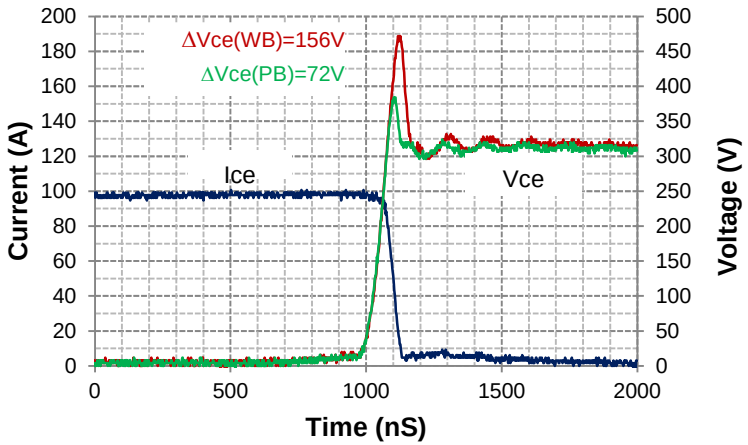
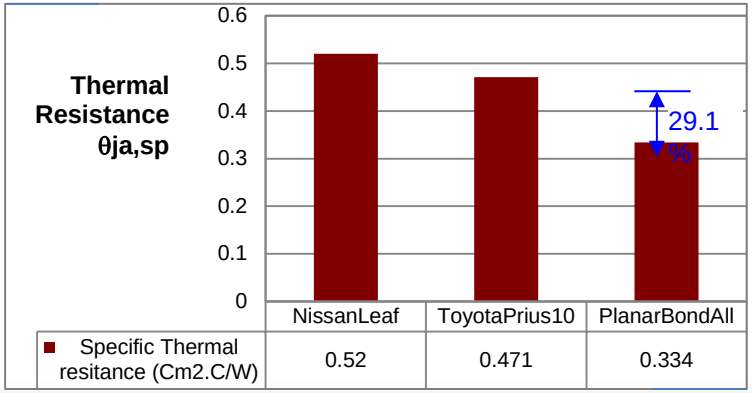
PBA Power Module







Advancement of PBA packaging technology and power modules:

- ✓Decreased package thermal resistance by 30%;
- ✓Decreased package parasitic electrical inductance by 3/4th, and electric resistance by 90%;
- ✓Reduced the major packaging manufacturing steps from five (5) to two (2);
- ✓Achieved more than 30% volume, and weight reduction.

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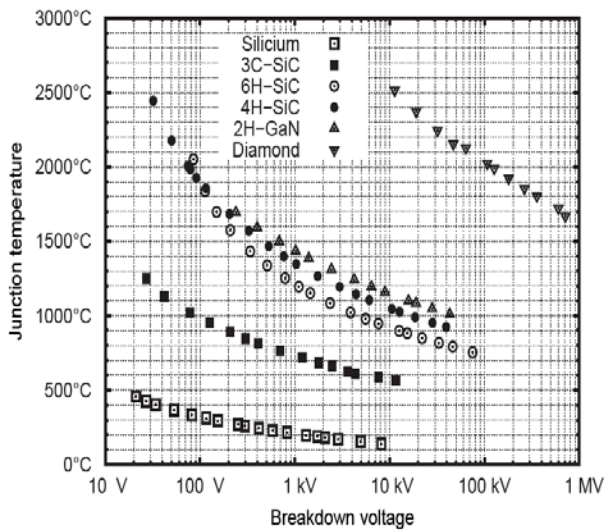
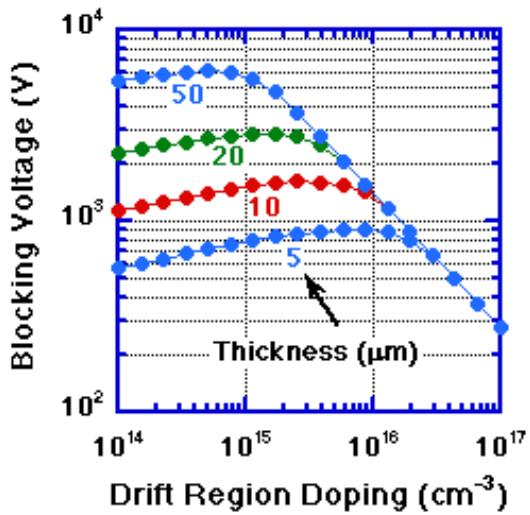
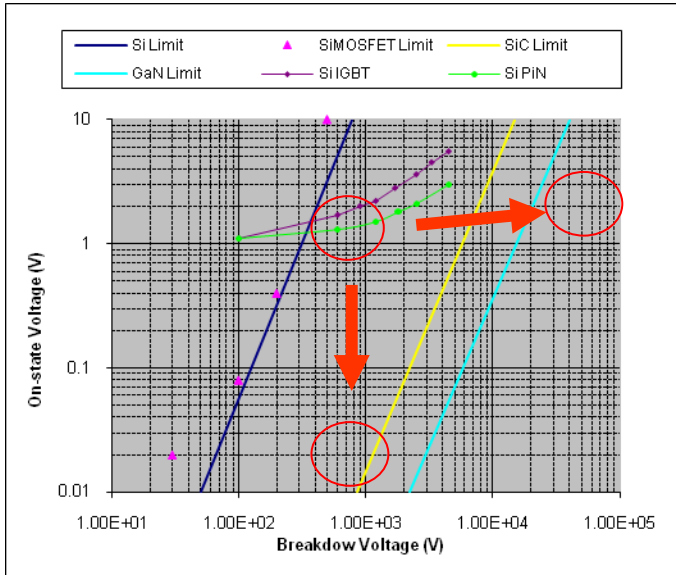
WBG Power Semiconductors

Property	Si	GaAs	SiC	GaN	Diamond
Bandgap, *Eg* (ev)	1.12	1.43	3.26	3.45	5.45
Breakdown Electric Field E_c (kV/cm)	300	400	2,200	2,000	10,000
Intrinsic Carrier Concentration n_i (cm^{-3})	9.65E9	1.8E6	1.6E-6	1E-7	1E-27
Electron Mobility μ_n (cm^2/V•s)	1,500	8,500	500-1,000	1,250	2,200
Hole Mobility μ_p (cm^2/V•s)	600	400	100-115	850	850
Dielectric Constant ε_r	11.9	13.1	10.1	9	5.5
Thermal Conductivity κ (W/cm•K)	1.5	0.46	4.9	1.3	22
Saturated Electron Drift Velocity υ_{sat} (10^7 cm/s)	1	1	2	2.2	2.7







100th Conduction Loss;100X Voltage Blocking;10th Switching Loss.

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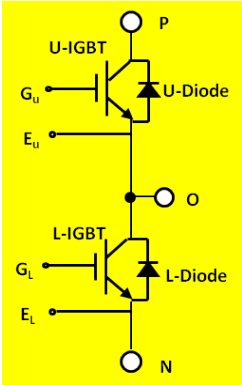
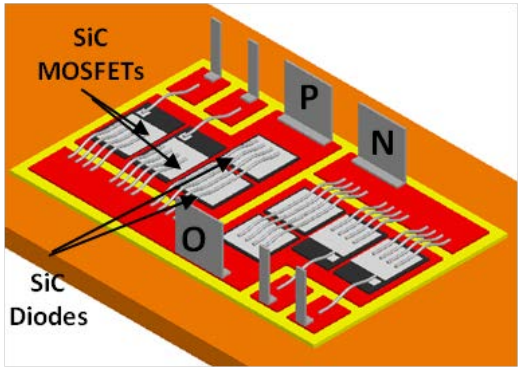
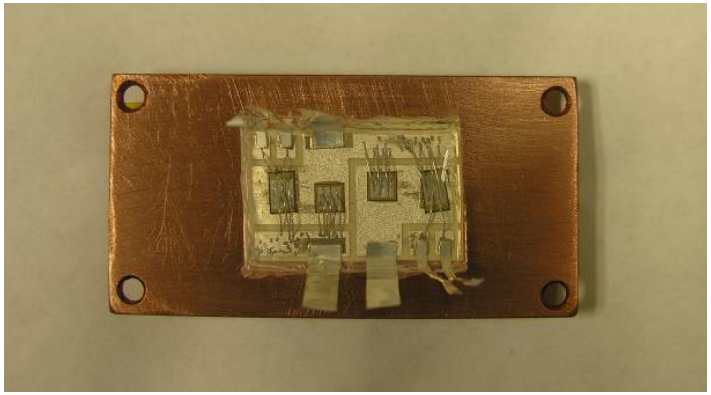
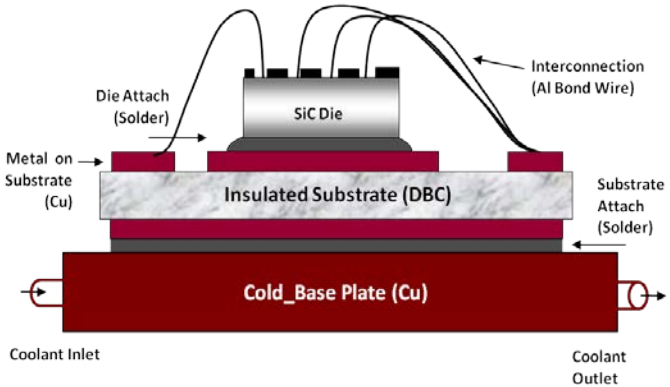
All-SiC Phase Leg Module Packaging

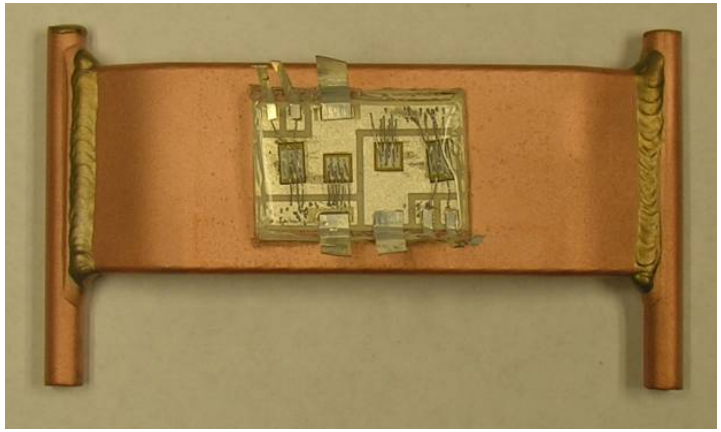




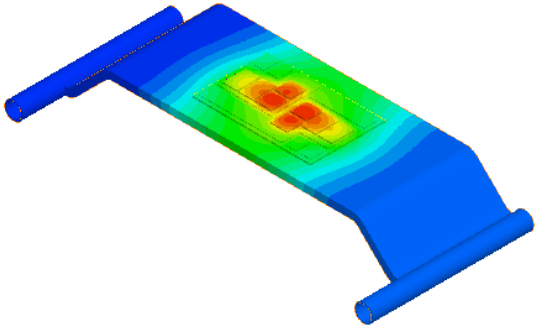


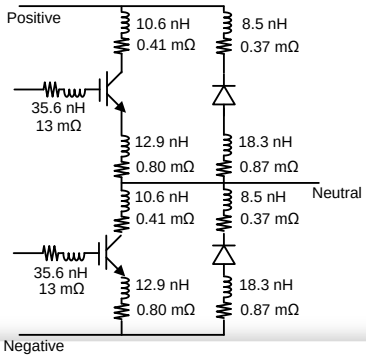
SiC Power Module with Conventional Cooling





SiC Power Module with Integrated Cooling





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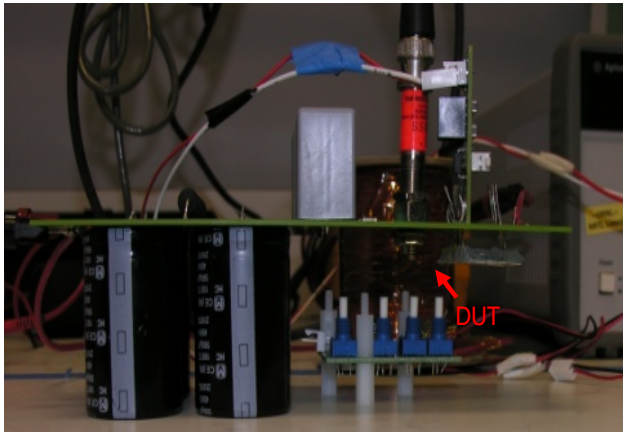
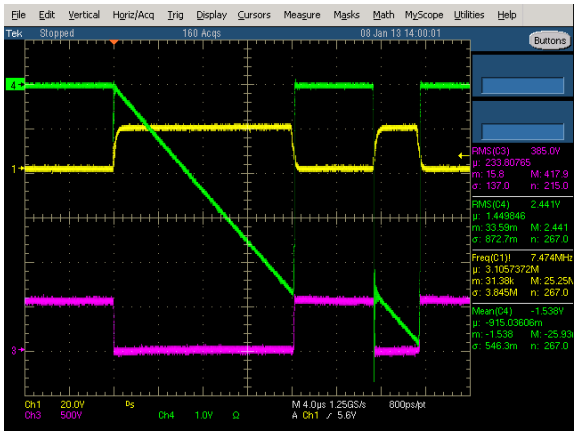
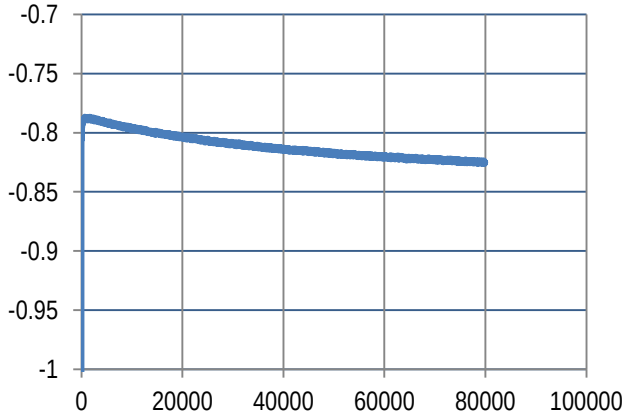
Characterization of SiC Modules



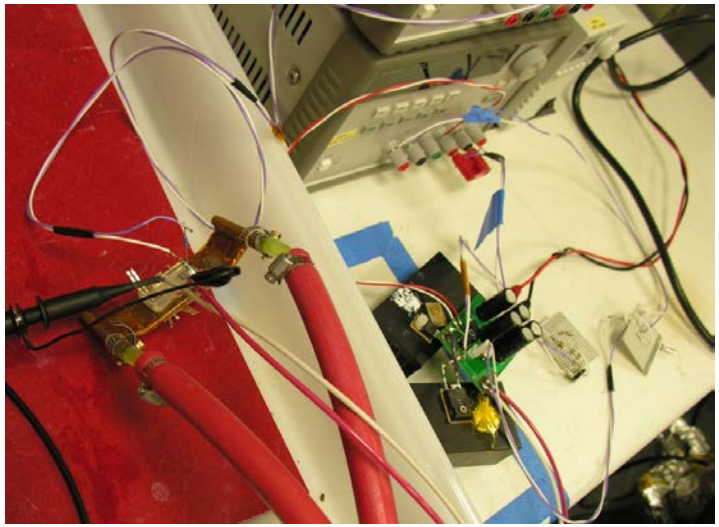
SiC module under electrical testing



SiC module Switching Waveforms



Vf decay of body diode in SiC MOSFET during cooling down phase



Packaged SiC module in thermal test setup

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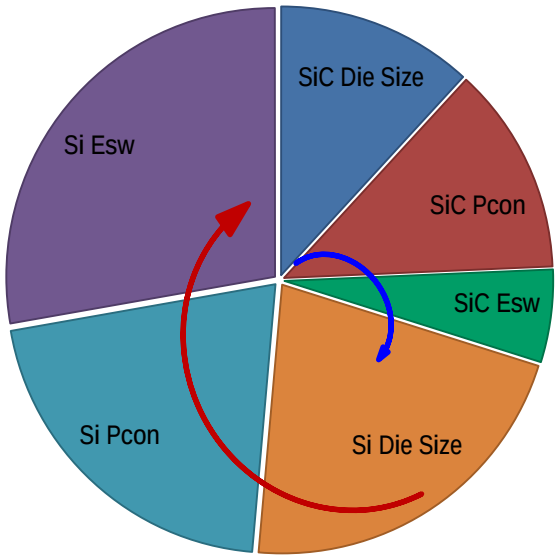
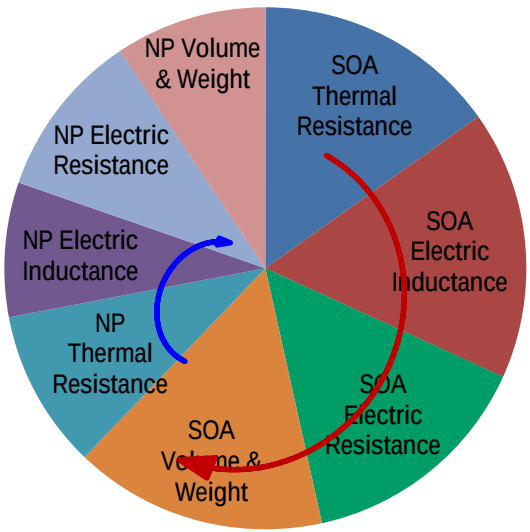
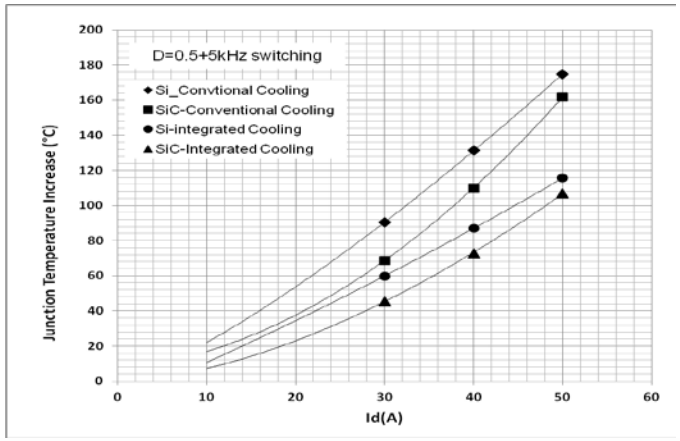
Module Performance Evaluation



SiC and Si Comparison



Packaging Comparison



Current density allowed for different power semiconductor and cooling combinations at ΔTj=100°C for a typical operation (D=0.5, f=5kHz)

Item	Si_Con. Cooling	SiC_Con. Cooling	Si_Integ Cooling	SiC_Integ Cooling
Current Density J_d (A/cm^2)	65.35	144.97	97.57	184.98

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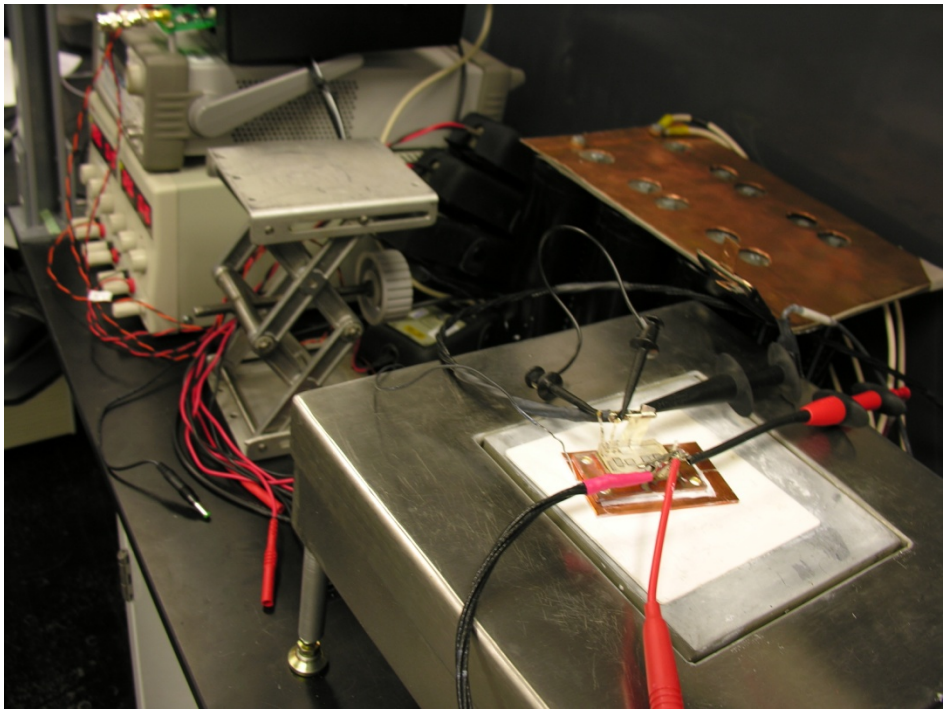
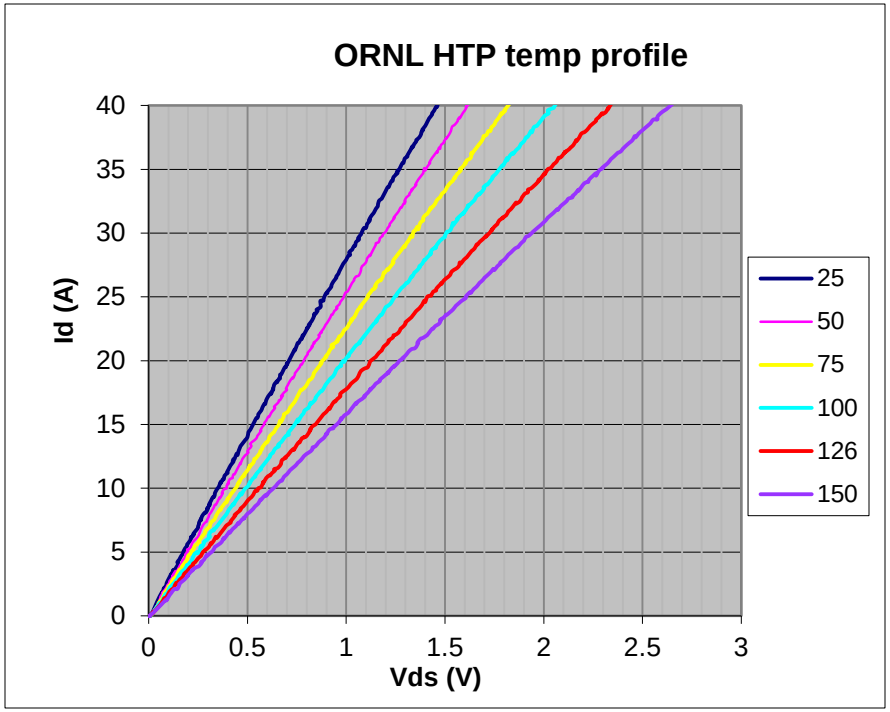
High Temperature Evaluation of SiC Power Module





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Summary

- **Power electronics are critical enabling factors to promoting electric drive vehicles (HEVs and EVs). Power packaging technologies have been advancing, with focus on improvements in cost, reliability, power efficiency and density through structure optimization, material and processing developments.**
- **The State-of-the-Art power modules feature less electrical parasitics, lower thermal resistance and enhanced thermo-mechanical properties to assure the reliability of power electronics in automotive harsh environments.**
- **It is envisioned that more advanced packaging structure/ material/process schemes will be developed and integrated for high temperature and high frequency operation of Si and wide bandgap (SiC, GaN) power devices for future automotive applications .**

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