Some Progress in Cooling and 3D Packaging for EV/HEV Inverters

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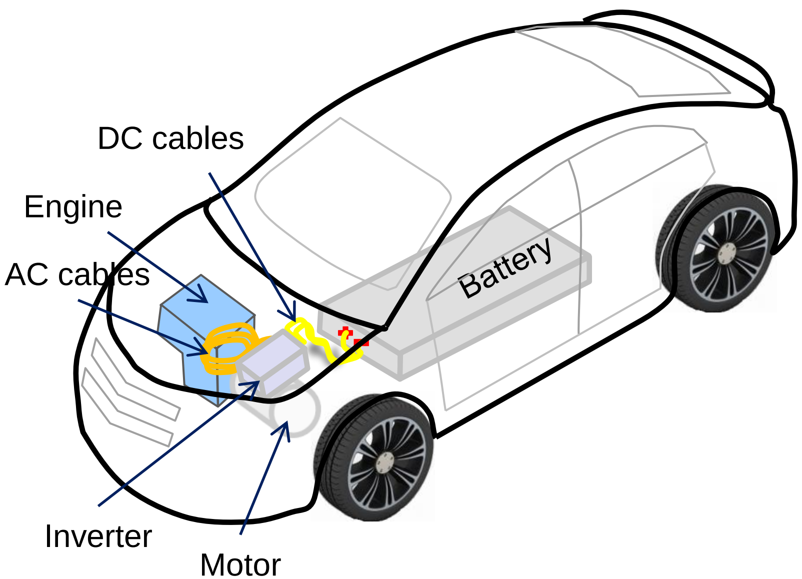
Outline

- Rapid progress in packaging technologies enables cheaper, smaller and more reliable EV/HEV inverter.
- More 3D integrated packaging solutions
  - From power module to the components below
  - From power module to the components above
- Fast adoption of more 3D integrated packaging technologies
  - Fast design iterations and short design cycles
  - EV/HEV inverter qualification testing are costly and time-consuming
  - More integrated inverter can still lead to higher cost due to testing alone
- Testing need to be well integrated with analysis (modeling) to lower the development cost

EV/HEV Inverter

- A critical component for electric powertrain system
- Typically convert 10~100 kW power from the battery to drive the motor

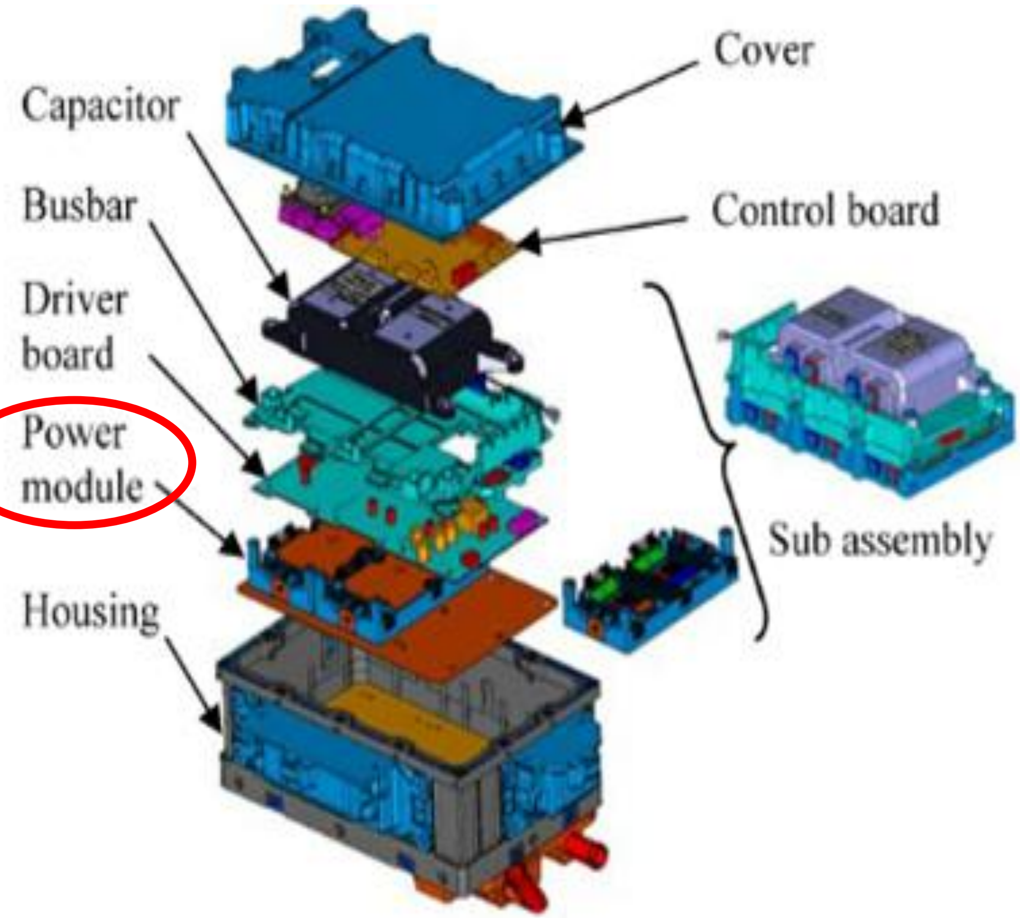


More 3D Integrated Solution

Integration from power module to the other components

3D up

3D down

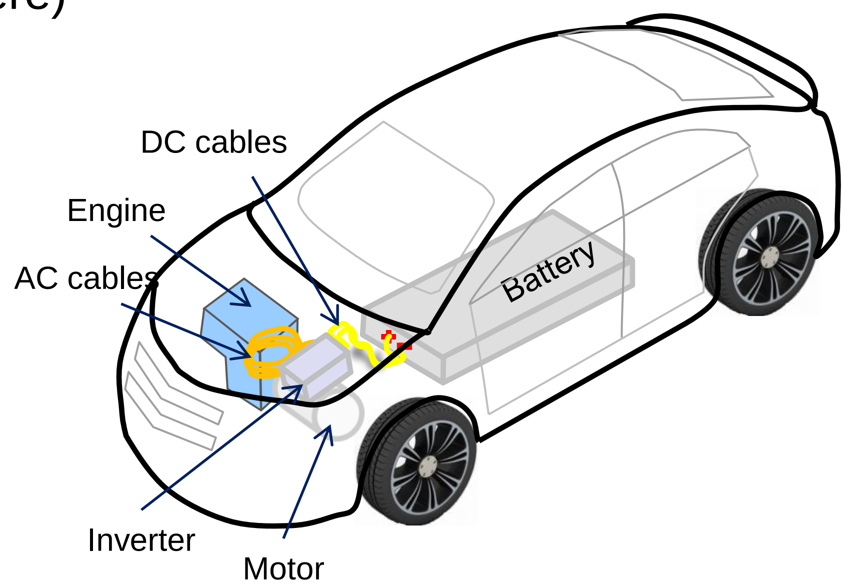


Ref 1 , 2

Trends

- ***Cheaper*** (~1/4 of Electric Powertrain cost)
- **Smaller (High power density) and lighter**
- **Reliability (15 years/100,000miles or even longer)**

  Under extreme mechanical and climatic conditions
  - Thermal related reliability due to high power
  - Environmental conditions: from Death Valley to Alaska
  - Vibrations (not discussed here)



“Emerging” Power Module Packaging Technologies

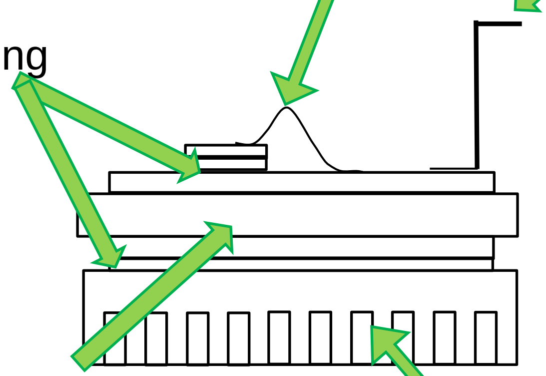
Enabler for lower cost, better reliability, smaller and lighter

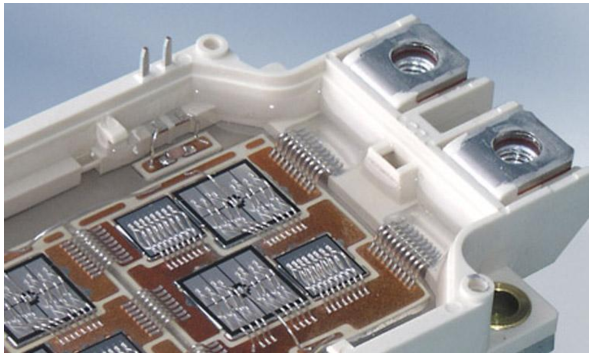
Al wire bond
- Cu Wirebond
- Sintering
- Direct Lead Bonding (Mitsubishi)
- Cu Pin (Fuji)

Bolted power connections
- Pressfit
- Spring

…

Joint (lead free solder)
- Sintering
- Diffusion soldering
- Brazing





Substrate (DBC)
- Non-ceramic based substrate
- DBA

Cooling:
- Double side cooling (Delphi, Hitachi, Toyota…)
- **Heat sink (Al)**

Cu VS Al Heat Sink

Both Cu and Al heat sink have been used in EV/HEV

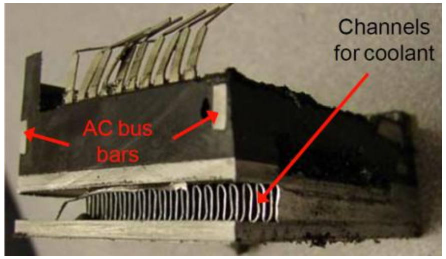
- Cu is preferred in high power power module over its excellent thermal conductivity
- Al has its advantages over cost, manufacturability, and density

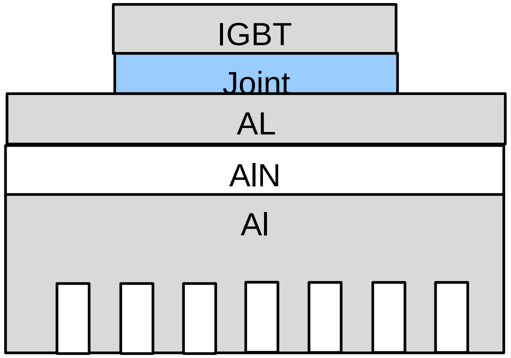
	Thermal conductivity (W/mK)	Density (g/cc)	CTE (10E-6/K)	Elastic Modulus (GPa)
Cu	385	7.76	16.4	110
Al	210	2.70	24	68

Al Heat Sink

- Al heat sink are becoming more popular in EV inverters
- Provided a more integrated solution between cooling manifold and heat sink
- Possibility of reducing process steps and components

Heat sink used in Nissan Leaf
(source : ORNL report)

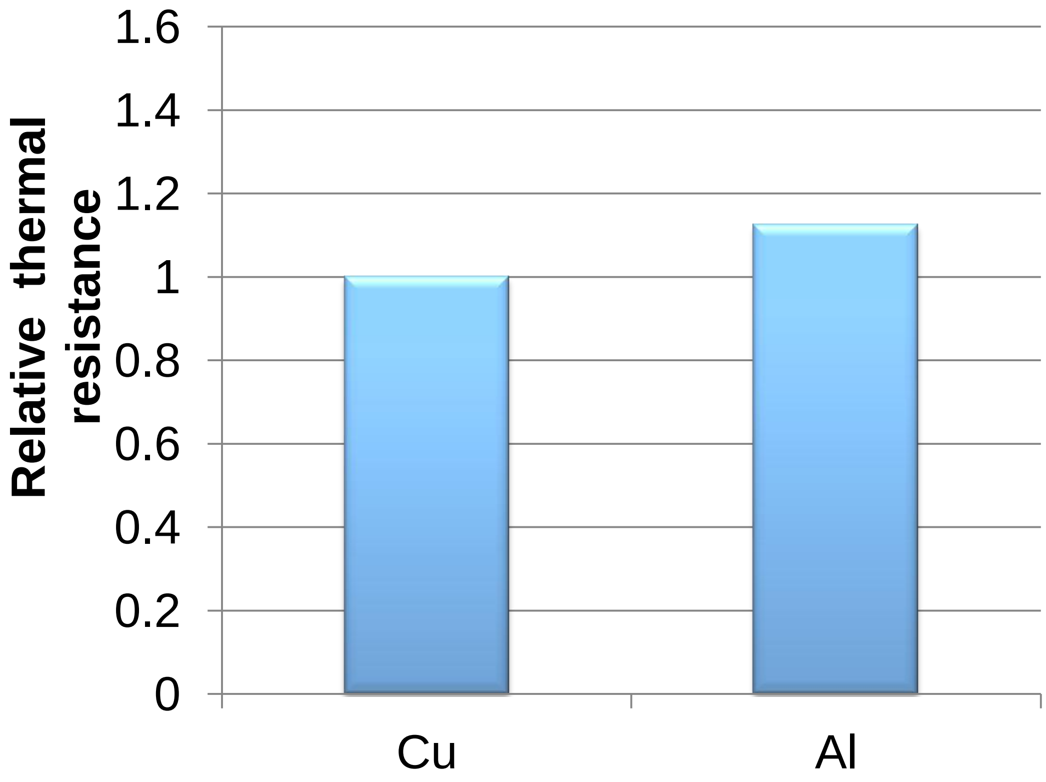


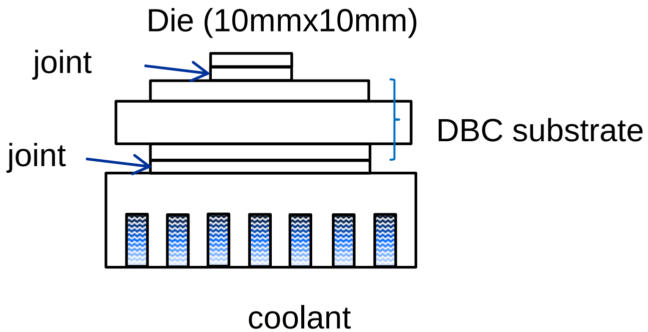


2010 Prius (Source: ORNL report)

Cu vs Al Thermal Resistance Comparison

- Although Cu has much better conductivity, thermal resistance of Cu heat sink typically only occupy 30~40% resistance of the whole power module stackup
- Cu provide better thermal performance, yet Al heat sink can be acceptable, depending on the requirement and the whole system optimization



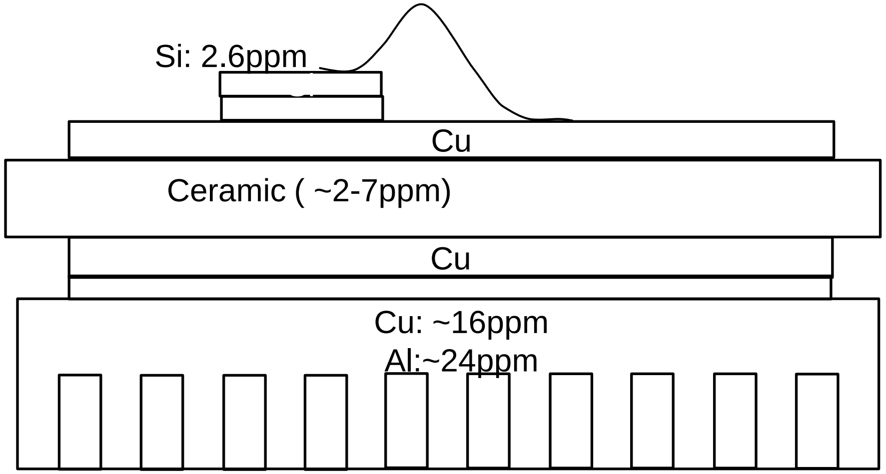


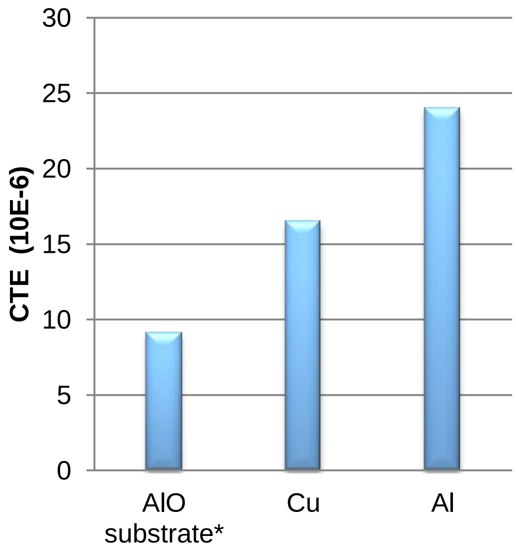
Forced cooling
50/50 Ethylene glycol /water

Analysis

Thermo-Mechanical Reliability

- Reliability is related to CTE mismatch and temperature fluctuations
- Typically Cu heat sink is related to better thermo-mechanical reliability
- Al heat sink can also have acceptable reliability if careful designed





* CTE of AlO substrate is estimated for 0.3mmCu/0.625mmAlO/0.3mmCu

Selection of EV/HEV Inverter Packaging Technology

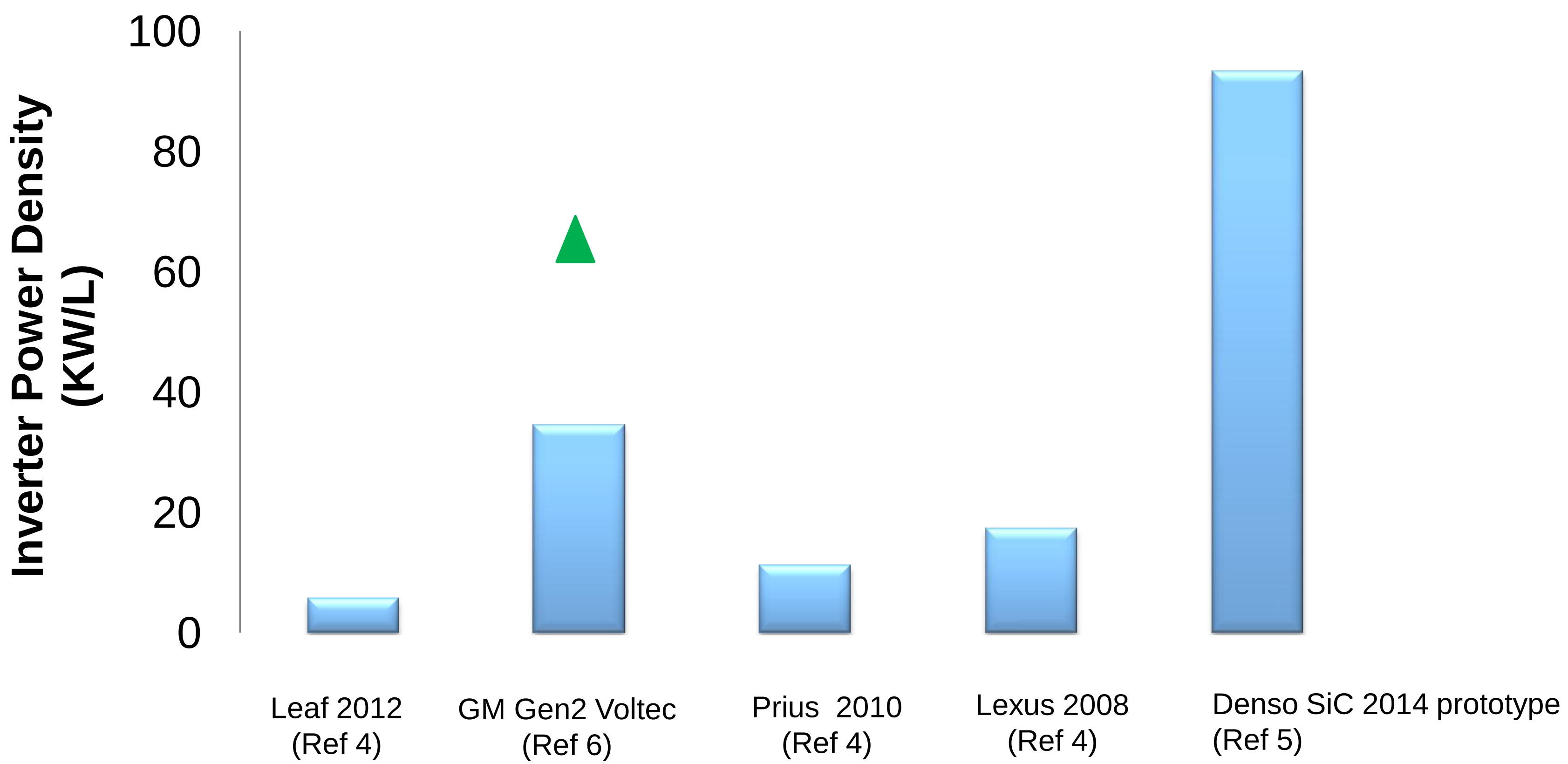
- Al heat sink is preferred as a more 3D integrated solution
  - Considering cost, performance, thermal, reliability and size
  - Based on the whole inverter system

- Limiting factor for inverter cooling system?

- **Power loss** is a major factor deciding inverter packaging design
  - Thermal (cooling)
  - Reliability (CTE mismatch, temperature change due to power loss on/off)
- Reducing power loss is the fundamental solution to increase inverter power density, improve reliability and reduce the cost

Reduce Power Loss is the Key to Improve Power Density

- Progress in packaging technology is helping , but still not enough(at most x2)
- SiC is one **possible** solution to significantly reduce power loss

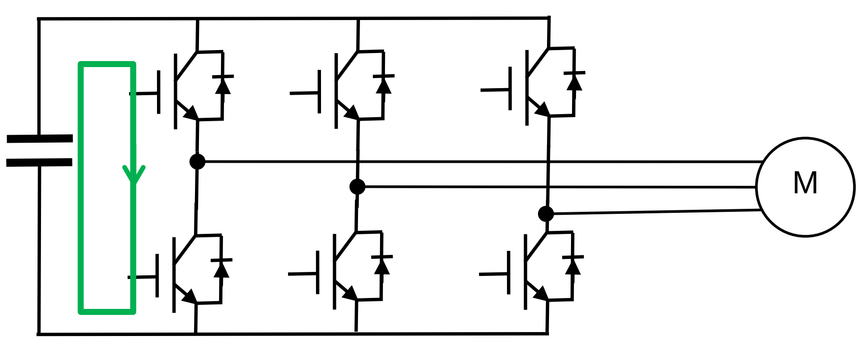


Impact of SiC on Inverter Packaging

- Increased efficiency (1/3 of power loss) *

  Significant reduce cooling needs (from forced liquid cooling to forced air cooling)*
- High switching frequency

  Packaging need to ensure low inductance loop between DC link and the switches

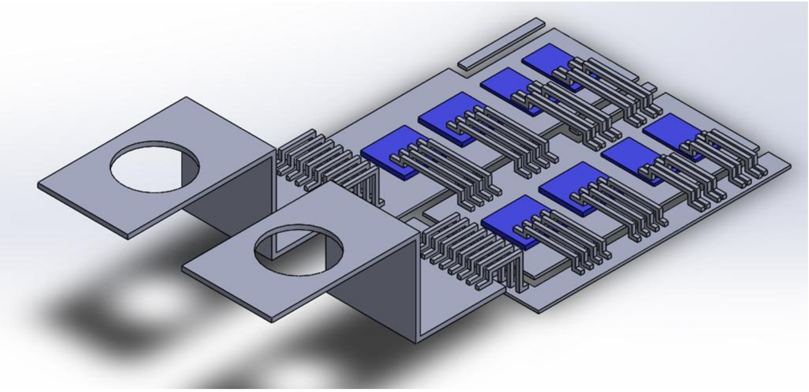


* Ref 5

3D Integration from Power Module to Capacitors

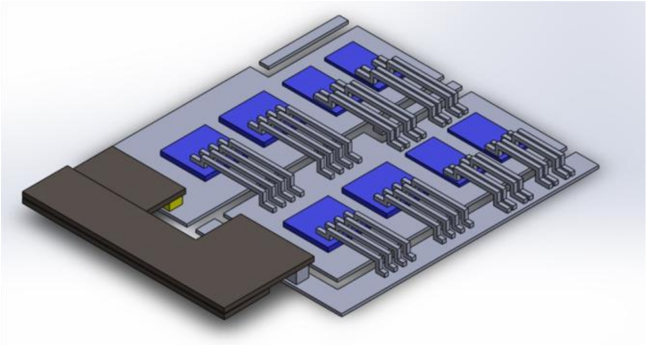
- Power module is more integrated with capacitor to ensure low inductance
- In traditional module a large portion of inductance comes from the bolted connections
- Several non-traditional packaging are potential solutions for low inductance

Concept 2 reduces the inductance by ~40% compared to concept 1



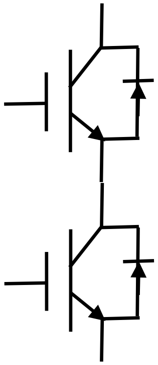
Concept 1

Traditional



Concept 2

Low inductance
(likely Double side, Cu stud, pressfit…)



ANSYS Q3D Simulation

Low Inductance SiC Power Module and Subsystems

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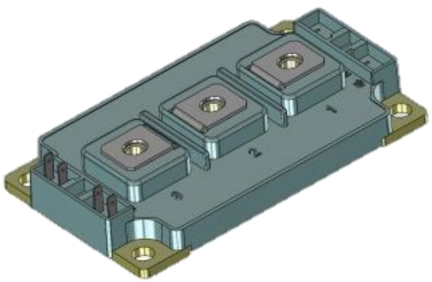
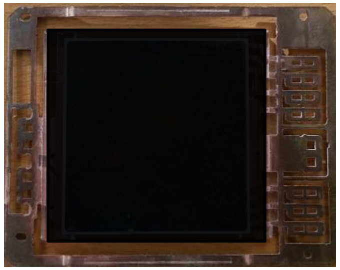


GPTG 1200V 320A SiC MOSFETs Half Bridge Module

- Low profile(17mm height)
- low inductance less than 10nH
- Ultra low power loss

GPTG 3.5kW On-Board Vehicle Charger

- Size = **2.9L displaced**
- Mass = **3.2kG**
- Conversion Efficiency => 94%



Under Development
Transfer molded ultra low inductance SiC power module
(automotive rated)

GPTG Ultra High Efficiency 50kW SiC Inverter

http://www.gptechgroup.com/pdf/PowerMax50.pdf

Visit Exhibitor Booth #1547

Challenges: Costly and Time Consuming Testing

Testing alone can cause more integrated inverter expensive, even with low process and material cost

- Testing is one major factor contributing to cost of EV/HEV inverter

Item \ Category	Industrial use	Automotive use
Temperature cycle test	100 cycles Temperature conditions : –40 to +125°C	1,000 cycles Temperature conditions : –40 to +125°C
Power cycle test	15,000 cycles Temperature conditions: ΔT_j = 100°C	30,000 cycles Temperature conditions: ΔT_j = 100°C
Vibration test	Acceleration = 10 G 2 h for each of X, Y and Z axes	Acceleration = 20 G 2 h for each of X, Y and Z axes

Power Module OEM's qualification test   Ref 18

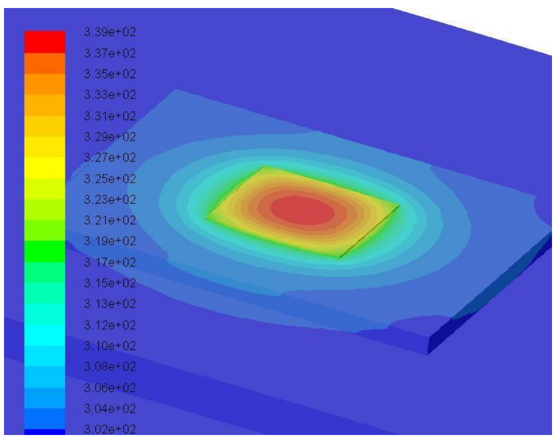
- More integrated inverter systems →more failure? more uncertainty?

1. Influence of more components: cooling components, capacitors…
2. Different failure mechanisms: sintering joint, press fit, …

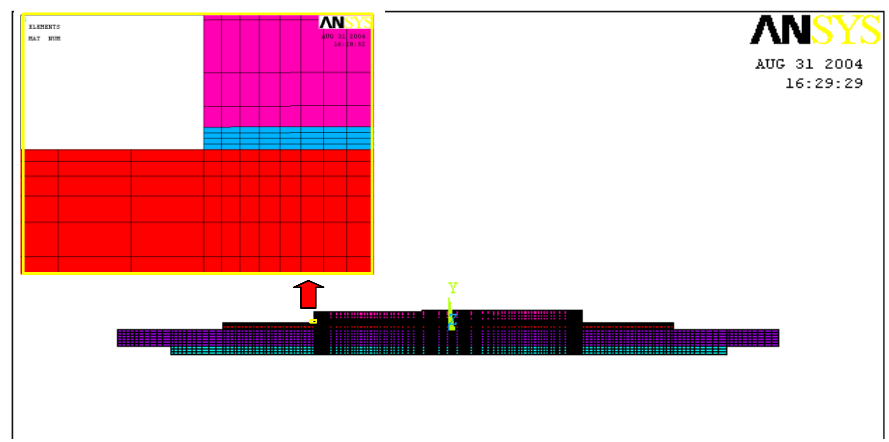
Testing Integrated with Analysis = More Efficient Testing

Analysis (modeling) helps to make design/testing more efficient in several area

- Thermal Analysis using analytical model or CFD
  - Cooling design
  - Temperature
- Thermo-mechanical analysis using analytical or FEM software
  Interconnect reliability
- Vibration analysis using FEM (resonant frequency)



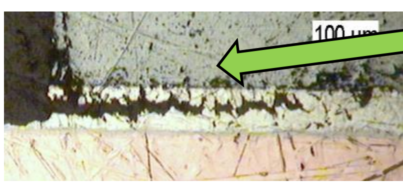
CFD analysis



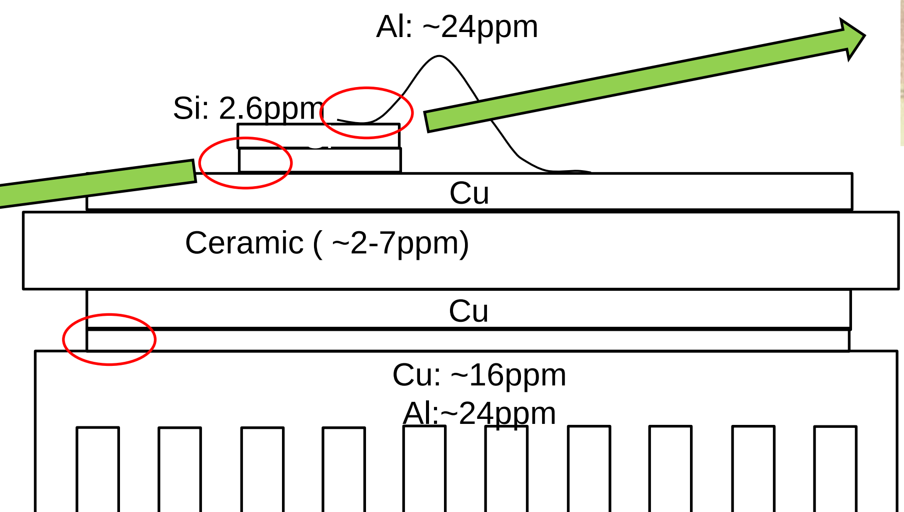
FEM analysis

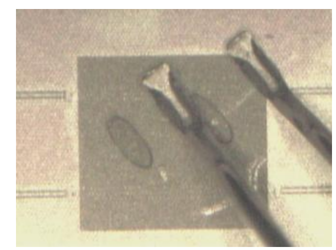
Thermo-Mechanical Analysis (Modeling)

- Interconnect reliability (wire bond, joint, …)
- Most failures share the **same fundamentals** and can be modeled at some level: **deformation due to CTE mismatch and temperature change**
- The level of modeling depends on the physics and individual process
  1. Design comparison in the early design stages
  2. It is possible to roughly estimate life for some process, but not always.
- For a lot of technologies, modeling is individual OEM process based
  - Solder joints
  - Sintering joints
  - …



Joint fatigue failure



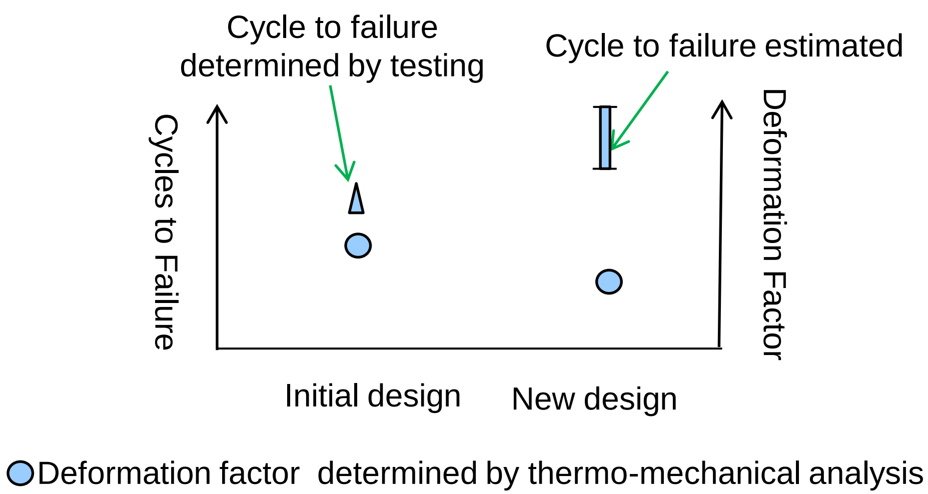


Wire bond failure

Example: Analysis to Reduce Test Iterations

Thermo-mechanical interconnect fatigue failure (non traditional package)

- Initial designed module failed before required cycles
- Roughly estimated the range of expected cycles to failure for new design based on the analysis and lessons learned
- Reached design goals in second round of testing



Summary

- EV/HEV inverter needs to be cheaper, smaller and reliable, not there yet
- In response, more 3D integrated packaging solutions are emerging
  - Power module integrated with cooling components
  - Power module integrated with capacitors
- Changes are inevitable and need to be rapid and reliable
- More integrated inverters can be expensive just because of testing alone
- In the long term, the winning low-cost inverters need to have analysis well integrated with testing
  - Optimize designs with fewer iterations
  - Fast/fewer test iterations

Acknowledgement

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